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Detection of the real joint interface between ultrasonically welded aluminium strands (Al-strands) and copper terminals (Cu-terminals) connections using non-destructive testing methods

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Abstract

The ongoing electrification of the automotive sector increases the demand for reliable and production-robust electrically conductive joints, particularly in cell interconnection, high-voltage wiring harnesses, and power electronics. Ultrasonic metal welding has become an established joining technology because it forms metallurgical solid-state bonds for material mixes without additional filler materials.

At present, the quality of ultrasonically welded joints is assessed primarily by destructive mechanical testing and simple limit value control. Although these destructive methods provide reliable information on weld quality, they are limited to sample-based inspection in series production and therefore permit only restricted testing intensity. Consequently, sporadically occurring defects may remain undetected. Against this background, advanced non-destructive testing methods are gaining increasing importance, as they enable the evaluation of joint quality without impairing component functionality and improve diagnostic reliability through a higher inspection frequency.

This study investigates various non-destructive testing methods for ultrasonic welded joints between copper terminals and aluminum stranded conductors. The focus lies on quantifying strand compaction by computed tomography and characterizing the effective bonded area using imaging and thermal methods. The findings enable a deeper characterization of the joining zone. Building on these results, the correlation between effective joint area and resulting shear tensile strength is investigated to improve quality prediction by AI-based systems in further studies.

Keywords

Non-destructive testing methods, Joint interface characterization, Quality monitoring, Al/Cu dissimilar joints

1. Introduction

The ongoing electrification of the automotive industry is leading to increasing requirements for electrical interconnection systems. Novel vehicle electrical system architectures, particularly the transition from 400 V to 800 V systems, enable a

significant increase in performance in electric mobility [1]. A major advantage of this development is the reduction of charging times [2], [3]. With 800 V vehicle electrical architectures, charging powers of up to 350 kW can be achieved at DC fast-charging stations [4], [5]. As a result of these high charging powers, electrical conductors and their contact interfaces are subjected to increased thermal and electrical loads. This technological transition is therefore associated not only with new performance requirements, but also with additional risks regarding operational safety.

A further development observed in recent years concerns the material selection for electrical conductors. Due to volatile and increasing copper prices, copper conductors are increasingly being substituted by aluminum conductors [6], [7], [8]. However, aluminum has a lower electrical conductivity than copper. For unchanged current-carrying capacity requirements, this results in larger required conductor cross-sections [7], [9]. At the same time, contact elements continue to be predominantly manufactured from copper alloys. Consequently, high performing aluminum-copper dissimilar joints are required, which impose specific requirements on the joining process due to the different material properties of the joining partners.

The combination of high charging currents, aluminum-copper dissimilar joints and increasing conductor cross-sections is raising the demand for reliable and long-term stable electrical connections. Ultrasonic metal welding has become established as a suitable joining process for these requirements [10], [11], [12], [13]. The solid-state process belongs to the category of pressure-based welding processes and enables the production of metallurgical bonds without the use of filler materials [14] and limited forming of critical intermetallic compounds

With the increasing requirements for aluminum-copper dissimilar joints, the relevance of suitable quality control methods is also growing. The assessment of joint quality is mainly performed using destructive testing methods, such as mechanical shear tensile tests [15]. Due to the destructive nature of these methods, in production only sample-based inspection of the joint quality is possible. Considering the sensitivity of the ultrasonic welding process to external influencing factors, such as contamination by oils or dust, a residual risk remains with regard to process and component reliability [16], [17].

One approach to reducing this residual risk is quality monitoring using non-destructive testing methods [18]. These methods enable an increase in inspection intervals up to continuous assessment of joint quality. In particular, the detection and characterization of the actual bonding area within the joining zone can represent a meaningful quality criterion. The bonding area has a decisive influence on the mechanical and electrical performance of the joint and can therefore be used to assess joint quality.

In the present study, the suitability of different non-destructive testing methods for detecting the bonding area of ultrasonically welded aluminum stranded conductor-to-copper terminal connections with large cross-sections is investigated. Based on this, it is evaluated whether conclusions regarding joint quality can be derived from the detected bonding area.

1.1. Joint Formation

Ultrasonic metal welding belongs to the category of solid-state welding processes. According to DIN 8593, the process is classified as a pressure welding process in which “mass” acts as the energy carrier [19]. Bond formation is based on the interaction of a static welding force and high-frequency mechanical vibrations [20]. These vibrations are introduced into the upper joining partner via the sonotrode, while the anvil and the hold-down devices serve as counter supports for the lower joining part [17], [15].

The bond formation in ultrasonic metal welding is a complex thermo-mechanical process. During welding, the formation of the joint cannot be directly observed from the outside. To describe the underlying bonding mechanisms, the welding process is divided into different process stages in literature. However, the individual models differ with regard to the material investigated, specimen geometries and measurement methods [14], [17], [21], [22], [23].

According to Gester, the ultrasonic metal welding process for stranded conductor-to-terminal connections can be divided into four consecutive process stages. These stages describe both the mechanical approach of the sonotrode toward the joining partners, the actual welding process and the subsequent detachment of the tool from the joint [17].

1. Approach movement of the sonotrode:

In the first stage, the sonotrode is moved toward the joining partners under a constant low pressing pressure. As soon as the sonotrode comes into contact with the stranded conductor and the feed movement largely comes to a standstill, this stage is terminated by the machine control system.

2. Pressure build-up and pre-compaction:

In the second stage, the predefined welding pressure is built up within a defined time interval, causing the stranded conductor to be pre-compacted between the sonotrode and the terminal. In parallel, a defined trigger point is monitored, and reaching this trigger point initiates activation of the ultrasonic generator.

3. Ultrasonic activation and bond formation:

Once the trigger point is reached, the ultrasonic generator is activated and the sonotrode oscillates with the predefined amplitude. Due to the combined effect of welding force, ultrasonic vibration, frictional heat and plastic deformation, the stranded conductor is further compacted, resulting in the actual bond formation between the strand and the terminal.

4. Return stroke and detachment of the sonotrode:

After the defined termination criterion has been reached, the ultrasonic generator is deactivated and the sonotrode is lifted by the return pressure. An additional ultrasonic pulse supports the detachment of the sonotrode from the produced joint before the welded assembly is released.

According to Gester, the actual bond formation predominantly takes place in stage III. The resulting joint quality is commonly assessed by means of the maximum achievable shear tensile force. This force is significantly influenced by the process parameters [17].

De Vries describes bond formation in ultrasonic metal welding as a three-stage process in which mechanical vibrations, plastic deformation and microstructural changes are closely coupled. Initially, the joining partners are set into vibration, while, due to surface contamination, only local contact points exist at surface asperities (stage 1). With the onset of ultrasonic vibration, shear deformation occurs, resulting in the disruption of oxide layers and the formation of metallic contact areas. At the same time, plastic deformation and heating lead to an increase in the contact area and to the formation of a continuous joint (stage 2). With further loading, overwelding occurs (stage 3), which leads to a reduction in joint strength due to decreasing mechanical stability [21].

Detailed investigations by Balz on Cu-Cu welds led to a new six-stage model. This model describes bond formation in ultrasonic metal welding as a continuous thermo-mechanical process characterized by a progressive increase in contact area and a reduction in relative motion [14].

At the beginning of the process, ultrasonic vibration causes relative motion between the joining partners during the transient stage, resulting in heating of local contact points. In the subsequent stage, contaminants are removed and oxide layers are disrupted by shear motion, thereby exposing metallurgically clean contact surfaces for the first time. With increasing frictional heat, thermal softening occurs, which promotes intensive plastic deformation and growth of the contact areas.

This is followed by dynamic recrystallization within the joining zone, which is initiated by elevated temperatures and mechanical loading. As the process progresses, the maximum bonded area is reached, corresponding to the optimum process state. Continued thermo-mechanical loading eventually leads to overwelding, which is characterized by microstructural changes, particularly static recrystallization, and an associated loss of joint strength.

Balz uses the relative movements between the individual workpieces and the welding tools as indicators of the respective process state. This allows the motion states occurring during the welding process to be assigned to the individual stages of bond formation. In later studies, Li and Balle confirmed the phenomenological stages defined by Balz for aluminum-copper dissimilar joints [13], [24].

The bond formation is primarily determined by the process parameters defined before the welding process [25]. The main setting parameters include welding amplitude, welding energy and welding force. In time-controlled processes, welding time is of particular importance instead of welding energy, as it determines the duration for which ultrasonic vibration and welding force act on the joining partners. The process parameters must not be considered independently, since welding amplitude, welding force and welding energy or welding time mutually influence each other and are subject to complex interactions [17], [26], [14].

In addition to the selected process parameters, external factors also influence bond formation. These include, in particular, the material, thickness and geometry of the joining partners and welding tools [27], [28]. These factors affect vibration transmission, deformation behavior and local heating during the welding process. The surface properties of the joining partners also have a significant influence on bond formation [29]. These include technical roughness, oxide layer thickness and residues present on the surfaces [30].

Furthermore, residues such as oil, grease or other process-related contaminants can impede the formation of metallic contact areas. Different rolling directions or manufacturing-related surface conditions of the joining partners can also influence frictional and deformation behavior. Bond formation in ultrasonic metal welding is therefore not determined solely by the selected machine parameters, but by the interaction of process parameters, material properties, component geometry and surface condition [12], [31], [32], [33].

1.2. Validation of ultrasonic welded joints

For ultrasonic metal welding, there is no generally applicable standard that comprehensively covers all possible applications. Instead, user- and application-specific specifications are commonly applied in practice. These specifications define requirements regarding the electrical, geometrical and mechanical properties of the welded joint.

Stranded conductor applications represent an exception. For ultrasonically welded stranded conductor-to-terminal connections, specific requirements are defined in USCAR38-2 [34]. The standard DIN EN IEC 60352-9 essentially reflects these requirements and therefore provides an important basis for the assessment of ultrasonically welded stranded conductor connections [35]. These standards provide a common foundation for the requirements of individual process users and their customers. The specified requirements include various assessment criteria. These initially comprise visual and geometrical characteristics, such as external damage to the stranded conductor or terminal, as well as the position of the weld spot and the alignment of the joining partners relative to each other. In addition, metallographic cross-section analyses can be performed, for example to determine the compaction ratio of the strands. Furthermore, electrical properties, such as electrical resistance, and mechanical properties, particularly peel strength or shear tensile strength, are used to assess joint quality [17], [34].

The evaluation of the bond quality of ultrasonically welded joints is currently based on a combination of non-destructive and destructive testing methods [14]. While optical and external inspections can detect visible damage or geometrical deviations, they do not provide a reliable assessment of the internal formation of the joining zone. A complete non-destructive determination of weld quality is therefore currently only possible to a limited extent [14], [17].

In industrial practice, joint quality is predominantly evaluated using mechanical characteristics. These include, in particular, the maximum test force determined in shear tensile or peel tests. However, due to the destructive nature of these methods, only a limited number of welded joints can be inspected. For a process such as ultrasonic metal welding, which is highly sensitive to disturbance variables, this leaves a residual risk that defective joints may remain undetected during series production [36].

For stranded conductor-to-terminal connections, quality assessment is further complicated by the random spatial arrangement of the individual strands. In combination with possible contamination on the strand surfaces, this can lead to significant variations in bond quality. To achieve high mechanical and electrical performance, a preferably large-area metallurgical bond between the compacted strands and the terminal is particularly important.

Currently, welding systems primarily monitor static process parameters such as welding force, welding amplitude and welding energy or, in time-controlled processes, welding time. These parameters describe the process sequence but allow only indirect conclusions regarding the actually formed bonding area. AI-based approaches therefore use additional process data to predict weld quality non-destructively [37], [38]. Another approach is the direct detection of the bonding area using non-destructive testing methods.

To date, the bonding area has often been evaluated after destructive shear tensile or peel tests based on the residues remaining on the terminal. However, this method is associated with uncertainties, since material adhesions or residues on the joining surfaces may be incorrectly interpreted as bonded areas [39]. Non-destructive detection of the actual bonding area therefore offers the potential to make the assessment of joint quality more objective and closer to the process.

1.3. Aim of this study

The focus of this work is the non-destructive testing of ultrasonically welded aluminum stranded conductor-to-copper terminal connections. The objective is to detect and evaluate the actual bonding area within the joint using different testing methods. The determined bonding area represents a key characteristic, as it significantly influences the mechanical load-bearing capacity and, consequently, the quality of the welded joint.

Based on the non-destructively obtained test results, conclusions regarding the joint quality are to be derived. Particular emphasis is placed on the correlation between the welded area and the shear tensile force determined in the shear tensile test. By linking imaging-based testing methods with mechanical characteristics, a deeper understanding of the relationship between the welding process, bonding characteristics and resulting joint strength is to be established. The investigated correlation is intended to determine to what extent the non-destructively detected bonding area can be used as an indicator of the mechanical strength of the joint.

In the long term, the findings obtained may contribute to a more efficient validation of ultrasonically welded aluminum-copper joints and to the targeted optimization of the underlying welding parameters.

The non-destructive nature of the applied testing methods enables an increase in inspection intervals. The investigated joints remain usable after testing and can be used for further analyses. This allows for more frequent quality monitoring and contributes to reducing the failure risk of ultrasonic welded joints.

Overall, this work aims to contribute to the development of reliable evaluation methods for ultrasonically welded aluminum stranded conductor-to-copper terminal connections. The non-destructive detection of the bonding area represents a promising approach for further improving both quality assurance and process optimization in the field of ultrasonic-welded joints.

2. Methods

In the present study, an experimental approach is pursued to investigate the actual bonding area of ultrasonically welded joints. The joints are characterized using various thermal and further imaging-based testing methods. This enables a differentiated analysis of the formed interface between the aluminum stranded conductor and the copper terminal.

Three test series were defined for the investigations. These differ with respect to the component geometries used and the selected welding parameters. All analyses conducted in this study refer to ultrasonically welded aluminum stranded conductor-to-copper terminal connections. This allows a comparative evaluation of different joint characteristics within a consistent material and joining system.

The individual test series and the welds produced within the scope of this study are described in detail in the following sections. Both the geometrical boundary conditions and the relevant process parameters are presented. This description provides the basis for the subsequent evaluation of the test results and for deriving possible correlations between the bonding area and the joint quality.

2.1. Experimental approach

For the production of the specimens in all test series P, A and B, aluminum alloy EN AW-1370 was used. The aluminum conductor had a nominal cross-section of 95 mm². According to DIN EN 573-3, EN AW-1370 is classified as a commercially pure aluminum alloy [40]. Due to its high electrical conductivity, this material is particularly suitable for applications in electrical conductors. An uncoated copper ETP terminal (Cu-ETP) was used as the joining partner. Since Cu-ETP is commonly used for electrical contact elements, the combination of an aluminum conductor and a copper terminal represent a dissimilar material joint that is highly relevant for electrical interconnection systems.

Test series P differs from test series A and B with regard to the contact geometry. The terminals used in test series P had smaller external dimensions and were designed to be narrower. At the same time, they had a greater material thickness. A detailed overview of the specimen geometries used is provided in Table 1. Test series P was used exclusively for preliminary investigations. These investigations served as an initial assessment of the applied testing methods with regard to their general suitability for detecting the actual bonding area. In particular, it was examined whether the respective methods enable a differentiation between bonded and non-bonded regions.

Test Series	Material: Stranded conductor	Material: Terminal (LxWxH)	Number of samples
P (Preliminary investigations)	EN AW-1370 Cross-section 95 mm ²	Cu-ETP 35 mm x 25 mm x 5 mm 35 mm x 25 mm x 4.7 mm 35 mm x 25 mm x 3 mm	n=3
A (Detailed investigations)	EN AW-1370 Cross-section 95 mm ²	Cu-ETP 50 mm x 36 mm x 2 mm	n=5
B (Detailed investigations)	EN AW-1370 Cross-section 95 mm ²	Cu-ETP 50 mm x 36 mm x 2 mm	n =5

Table 1: Overview of the welding configurations for the test series

As shown in Table 1, the specimens of test series P were processed with three different terminal thicknesses. However, the specimens were initially manufactured using Cu-ETP terminals with an initial thickness of 5 mm. The different terminal thicknesses were subsequently achieved by mechanical post-processing of the contact elements after welding.

This procedure was chosen because some of the applied testing methods are sensitive to the anvil marks on the rear side of the contact element. These marks are generated during the ultrasonic welding process and necessary for many applications. They might affect the evaluation of the test signals and thereby impede the detection of the actual bonding area. By mechanically machining the terminals after the welding process, the extent of the anvil marks was deliberately reduced. This was intended to investigate whether the bonding area can still be reliably identified when the anvil marks are reduced or no longer pronounced. The machined specimens therefore allow an assessment of the influence of rear-side surface structures on the respective testing method.

Test series A and B were subsequently carried out only for those non-destructive testing methods that allowed an assessment of joint quality based on the bonding area. Testing methods that did not provide sufficient information regarding the bonding area were not pursued further.

This approach enabled a stepwise evaluation of the testing methods. First, their general applicability was assessed based on preliminary investigations. Subsequently, further analyses were performed on test series A and B, with a focus on a reliable evaluation of joint quality.

All ultrasonic welds within the test series were produced using optimized welding parameters. For this purpose, a Schunk Sonosystem LS-C equipped with a 9 kW generator was used. The parameter determination was based on a statistical design of experiments. Initially, preliminary trials were carried out to define a suitable parameter range for the welding process. Based on these trials, a central composite design was generated, performed and evaluated. In a second iteration, the experimental design was repeated with a slightly shifted and reduced parameter range. The new center point of the parameter study corresponded to the optimum parameter set identified in the first iteration. Due to the identical component geometries, the welding parameters for test series A and B were based on a common statistical design of experiments. The parameter determination for test series P was carried out separately.

Within the parameter study, the influence of welding pressure, amplitude and energy on the shear tensile force was investigated. The corresponding relationships are shown in the contour plots in figure 1.

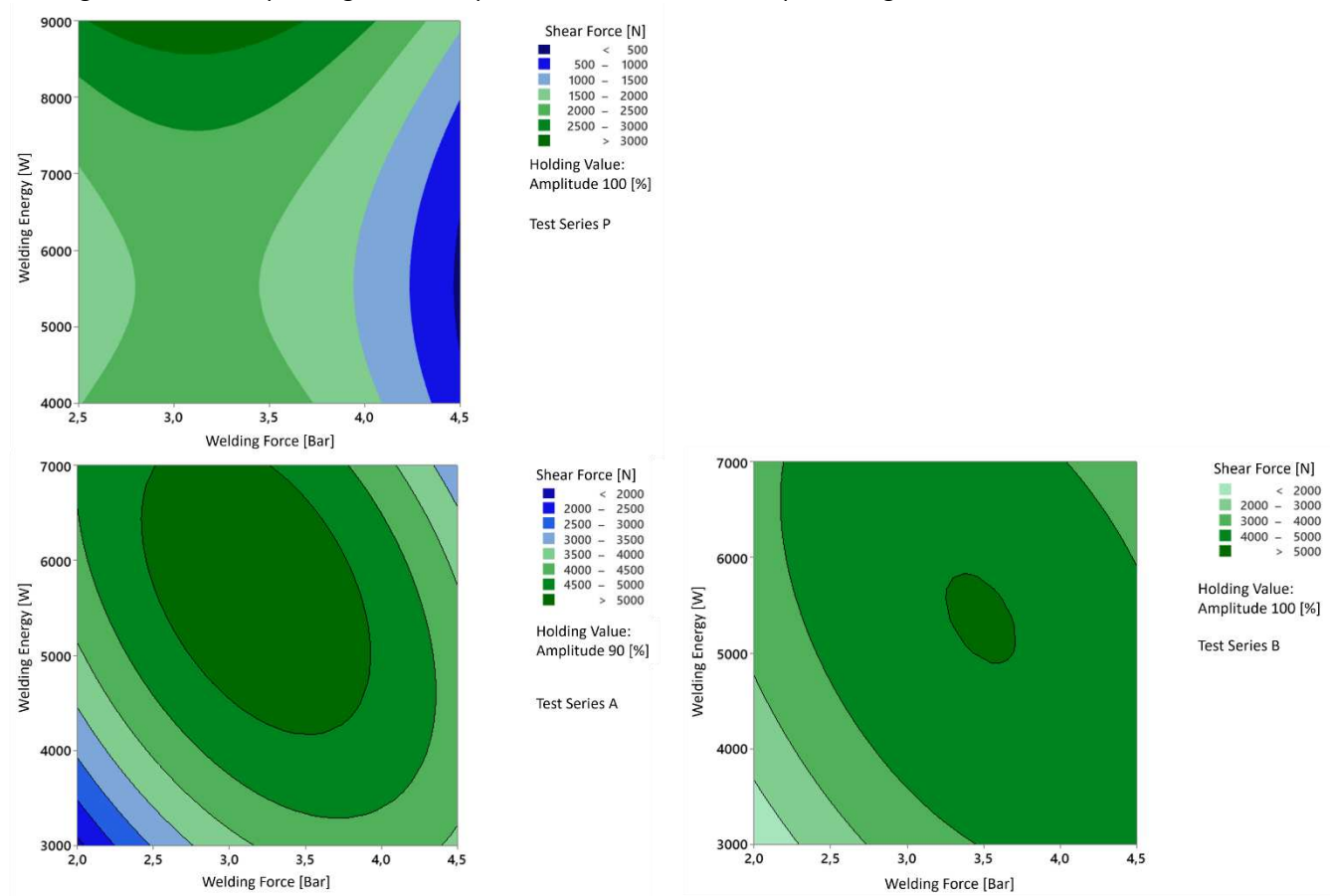


Figure 1: Factor diagram for determining the optimum welding parameters for test series P, A and B at a constant amplitude

The figure illustrates the interactions between the investigated process parameters and the resulting mechanical joint strength. The welding parameters used for specimen production in this study are summarized in Table 2.

Test Series	Welding Pressure [Bar]	Amplitude [%]	Welding Energy [W]
P	2.8 (n=3)	100% (n=3)	9000 W (n=3)
A	3.0 (n=3)	90% (n=5)	5000 W (n=3)
	3.2 (n=2)		5500 W (n=2)
B	2.0 (n=5)	100% (n=5)	2000 W (n=3)
			1500 W (n=2)

Table 2: Welding parameters used for test series P, A and B

Since the present study investigates the suitability of different non-destructive testing methods for detecting the actual bonding area, test series A and B differ significantly regarding the selected welding parameters. Test series A comprises good welds according to the required shear tensile forces specified in SAE/USCAR38-2. In contrast, test series B consists exclusively of bad welds [34]. Within test series A and B, the selected welding parameters vary slightly from one specimen to another. This small variation was introduced to determine whether the bonding area already changes because of minor parameter variations within the same quality class.

In general, the study aims to investigate the extent to which the detected bonding area differs between different quality classes of the welded joint. The targeted variation of joint quality therefore forms the basis for evaluating the testing methods regarding their informative value concerning the bonding area and the resulting joint quality.

2.2. Sample geometry and system configuration

The component geometries of test series A, B and P are described in detail below. In addition, the welding system setup used to manufacture the specimens required for the investigations is presented. As described in the previous section, test series A and B differ from test series P solely regarding the terminal geometry used.

The terminals of test series P have a length of 35 mm, a width of 35 mm and a material thickness of 5 mm. In contrast, the joining partners of test series A and B have a length of 50 mm, a width of 36 mm and a material thickness of 2 mm. The total conductor length of all specimens is 200 mm, of which 23 mm are stripped. This results in a free conductor length of 177 mm. The specimen geometries used for the individual test series are schematically illustrated in the following figure 2.

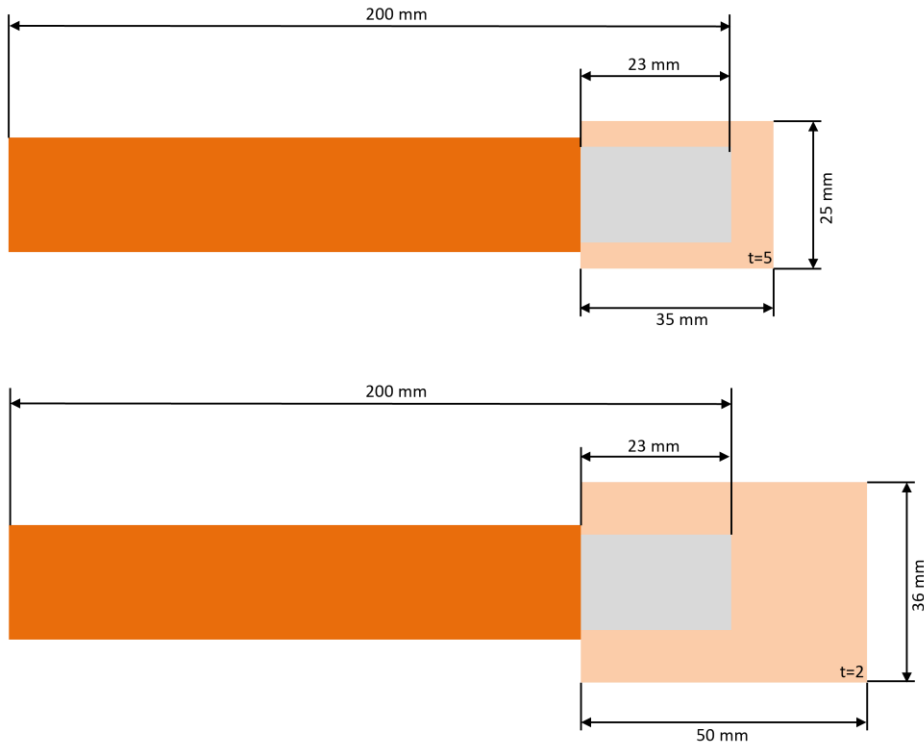


Figure 2: Geometry and welding position of the test specimens

The welds are produced with a reference overlap of 23 mm. The aluminum stranded conductor is positioned centrally on the Cu-ETP terminal. In preparation of welding, the contact elements are aligned in a positioning fixture. Subsequently, the joining partners are fixed by pneumatic hold-down devices applying a pressure of 4 bar. This ensures reproducible positioning of the joining partners during the welding process.

All welds are produced using a Schunk Sonosystem LS-C equipped with a 9 kW generator. The exact welding system configuration and the relevant system components are summarized in the following table.

Test Series	Sonotrode	Booster	Generator
A, B und P	λ sonotrode 22 mm working width	1:1	9 kW

Tabel 3: System configuration for sample preparation

3. Results

Initially, the operating principles of the non-destructive testing methods used in this study are briefly described. Subsequently, the results obtained with the individual methods are presented and discussed. This enables a method-specific assessment of the achieved measuring results.

Based on these results, the suitability of each testing method for detecting the actual bonding area between the aluminum stranded conductor and the Cu-ETP terminal is evaluated. The main focus is on whether bonded and non-bonded regions within the joining zone can be reliably distinguished. Subsequently, it is assessed whether the respective method allows an evaluation of the joint quality. If a testing method fulfills both criteria, a further detailed analysis is performed using test series A and B. Testing methods that do not provide sufficient information regarding the bonding area or the joint quality are not considered further.

Finally, the suitable non-destructive testing methods are compared with each other. Their informative value, applicability and sensitivity to the formed bonding area are evaluated. In addition, a correlation is established between the non-destructively detected bonding area and the shear tensile force determined by shear tensile testing. This is intended to verify to what extent the bonding area can be used as a characteristic parameter for assessing the mechanical joint quality.

3.1. Thermal test methods

The fundamental suitability of thermography for investigating ultrasonically welded aluminum stranded conductor-to-copper terminal connections is based on the relationship between local bonding and heat flow within the joining zone. A formed bond between the aluminum stranded conductor and the copper terminal enables improved heat transfer across the interface. In contrast, regions with no bonding or only insufficient bonding act as thermal barriers. As a result, local differences in the temperature distribution can occur, which can be detected by thermographic methods [41].

Thermography therefore offers the possibility of evaluating the joining zone based on its thermal response. When heat is introduced into the joint, its propagation is largely governed by the contact quality between the joining partners. Well-bonded regions conduct heat more efficiently than poorly bonded regions [42], [43], [44].

This relationship is particularly relevant for ultrasonically welded aluminum-copper joints. The actual bonding area is formed locally during the welding process as a result of plastic deformation, friction and interfacial activation. Consequently, it is not homogeneously distributed over the entire contact area. Thermographic testing methods enable a spatially resolved assessment of these inhomogeneities.

The suitability of thermographic testing methods for detecting the bonding area therefore results from the direct dependence of heat flow on the local interface quality. A good metallurgical bond promotes heat transfer, whereas defects, gaps or insufficiently welded regions impede thermal transport. The resulting temperature differences form the basis for identifying the actual bonding area between the aluminum stranded conductor and the copper terminal [41], [43], [45].

In addition to their potential for distinguishing bonded from unbonded regions, thermographic inspection methods present several challenges. The thermographic examination of ultrasonically welded aluminum stranded conductor-to-copper terminal joints is particularly complicated by the different thermophysical properties of the two base materials. For transient heat transfer across the Al-Cu interface, thermal effusivity is of particular relevance:

$$e = \sqrt{\lambda * \rho * c_p}$$

where λ denotes the thermal conductivity, ρ the density, and c_p the specific heat capacity. Thermal effusivity characterises the ability of a material to absorb heat or transfer it to an adjacent material under transient thermal loading. Owing to the different effusivities of aluminium and copper, a material-induced thermal contrast may occur even at a fully bonded and defect-free interface.

The inherent effusivity discontinuity at the Al-Cu interface may overlap with the thermal responses caused by pores, gaps, or unbonded regions, thereby affecting the measured thermal signal. Consequently, potential thermal reflection mechanisms may prevent an unambiguous attribution of a measured temperature or phase contrast to a defect, as the observed response may originate from both the transition between the two materials and the local interfacial condition. Further limitation arises from the high thermal diffusivities of aluminum and copper. Locally introduced heat is rapidly distributed throughout the copper terminal and the aluminum strands. This rapid heat diffusion smooths local temperature gradients and reduces the signal amplitudes associated with defects. Consequently, small or deeply located unbonded regions are often difficult to resolve and distinguish thermographically.

Intermetallic phases represent an additional potential challenge. Their thermophysical properties may differ substantially from those of the aluminum and copper base materials and may therefore alter heat transfer across the interface. Consequently, an intermetallic reaction layer could contribute an additional thermal resistance or property gradient, further complicating the interpretation of temperature and phase contrasts. In the case of ultrasonic metal welding, however, the presence and significance of such phases should be verified by appropriate metallographic or microanalytical investigations [17].

A further challenge in thermographic inspection is the reliable detection of subsurface defects. Defect detectability is primarily governed by the ratio of the lateral defect dimension d to the defect depth z . The corresponding aspect ratio is defined as

$$\Gamma = \frac{d}{z}$$

The larger and closer to the surface a defect is, the more strongly it affects the heat flow and the resulting surface contrast. Conversely, small or deeply located defects are increasingly thermally bypassed by lateral heat diffusion. This effect is

particularly pronounced in highly conductive materials such as aluminum and copper. Therefore, the condition $d/z \geq 1$ should be regarded only as an empirical rule of thumb rather than a universally valid detection limit.

For the detection of the actual bonding area, the non-destructive testing methods laser thermography and lock-in thermography were selected. Both methods enable contactless analysis of the thermal response of the joint. In the following sections, the operating principles of these methods are described and the corresponding experimental results are presented.

3.1.1. Laser Thermography

Laser thermography is a non-destructive and contactless testing method. It enables the spatially resolved acquisition of temperature distributions on a component surface and is particularly suitable for the rapid detection of near-surface inhomogeneities or defects [46]. The basic principle is based on the fact that defects, material inhomogeneities, or insufficiently bonded regions can influence the local heat flow within a component [43]. These changes result in measurable temperature differences at the surface, which can be recorded using an infrared camera [44].

Laser thermography is classified as an active thermographic testing method and uses a laser as a defined excitation source to introduce heat locally into the component surface. The generated thermal excitation propagates through the material and is influenced by the thermal conductivity, heat capacity, and geometrical as well as structural properties of the component. If defects, cracks, voids, interfaces, or insufficiently bonded regions are present, the local heat flow can be disturbed. These disturbances lead to deviations in the temperature distribution at the surface, which can be recorded by an infrared camera with both temporal and spatial resolution. Based on the temporal evolution of the temperature change, conclusions can be drawn regarding the internal condition of the component. Regions exhibiting deviating thermal behavior may therefore indicate defects or incomplete bonding between the joining partners [44], [46]. The schematic setup of laser thermography is shown in the following figure 3, while the experimental parameters used are summarized in the corresponding table 4.

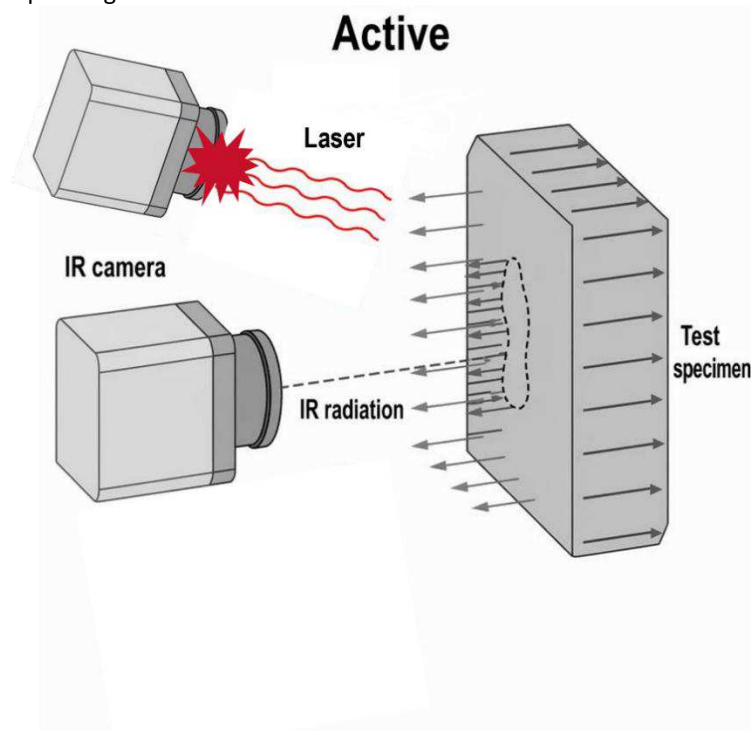


Figure 3: Schematic illustration of the laser thermography system

Technical Parameter	Specification
Laser thermography System	edevis LTvis / LTscan
Laser	IPG Photonics YLR
Laser wavelength	1070 nm

Laser amplitude	100%
IR camera frame rate	300 Hz
Integration time	670 μ s
Scanning method	Area scan
Scan pattern	Line scan pattern
Scan velocity	0.4 m/s
Line spacing	0.3 mm
Diffusion time	50 s

Table 4: Technical specifications and scanning parameters of the laser thermography system

Laser thermography investigations show that, under the selected testing conditions, this method does not allow reliable detection of the actual bonding area in ultrasonically welded aluminum-copper dissimilar joints. The time-resolved representation of the thermal response of the copper terminal clearly indicates a measurable temperature increase resulting from the local laser excitation. However, a spatially resolved differentiation between bonded and non-bonded regions within the joining zone could not be achieved. The following figure 4 illustrates the temporal evolution of the thermal response to laser excitation.

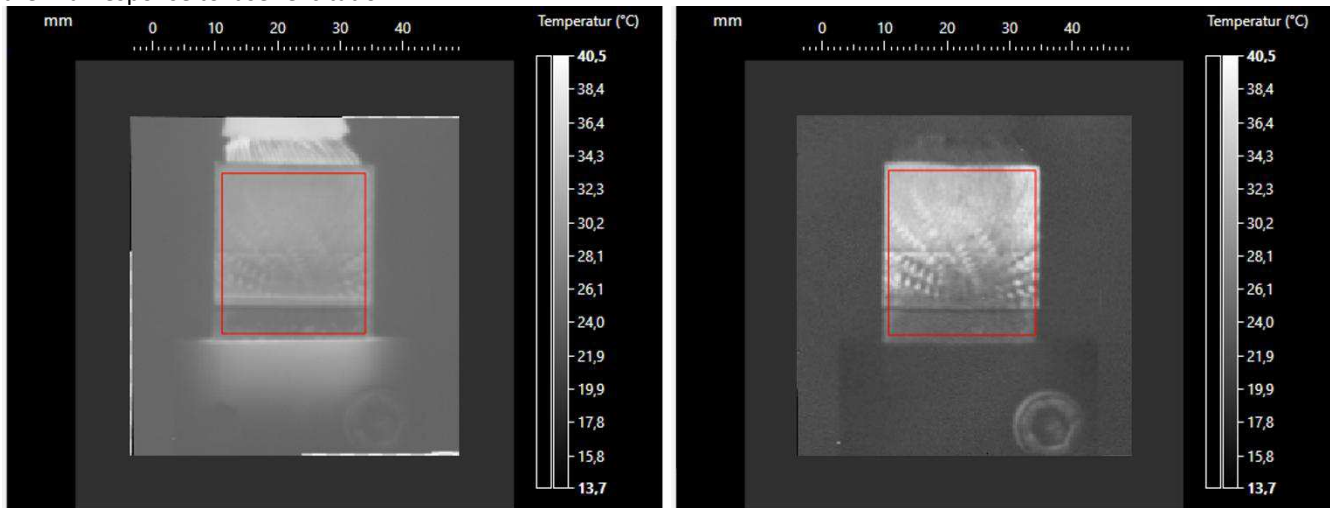


Figure 4: Time-dependent evolution of the thermal response of the Cu terminal to laser excitation

Instead of local thermal contrasts, a largely homogeneous heating of the entire terminal can be observed during the excitation period. The heat introduced locally by the laser spread very rapidly within the copper terminal, resulting in a spatially distributed temperature field. Consequently, the thermal response is primarily governed by the high thermal conductivity of copper. Local variations in heat flow that could potentially arise from non-bonded regions within the joining zone are superimposed by the rapid lateral heat propagation and are not represented at the surface with sufficient contrast. This behavior is particularly disadvantageous for the detection of the bonding area. The principle of laser thermography requires bonded and non-bonded regions to form different thermal conduction paths, resulting in measurable temperature contrasts at the surface.

Additional investigations with removed anvil marks and reduced terminal thicknesses did not lead to a significant improvement in the measurement results. Although removing the anvil marks reduced potential effects of surface topography, it did not improve the representation of the joining zone. Likewise, reducing the terminal thickness did not sufficiently increase the thermal contrast. This confirms that the limited detectability of the bonding area is mainly caused by the high thermal conductivity of copper and the resulting rapid heat distribution.

In summary, laser thermography is not suitable for determining the actual bonding area in ultrasonically welded aluminum-copper dissimilar joints. The changes in heat flow caused by non-bonded regions are too small to enable a reliable distinction between bonded and non-bonded zones. Therefore, an assessment of joint quality based on the laser thermography results is not possible. Consequently, this method is not considered further in the subsequent investigations.

3.1.2. Lock-In Thermography

Lock-in thermography is classified as an active thermographic testing method. In this approach, the test object is deliberately thermally excited by an external energy source. The primary excitation signal is introduced into the component in a periodically pulsed or amplitude-modulated manner. The modulation frequency used for this purpose is referred to as the lock-in frequency [44].

Halogen lamps are used as the excitation source. These generate a periodic heat input at the component surface. The introduced heat propagates through the material and is influenced by the thermal properties of the material as well as by possible inhomogeneities. As in laser thermography, defects, cracks, voids or insufficiently bonded regions can locally disturb the heat flow. This results in differences in the thermal response of the component, which are recorded with temporal resolution using an infrared detector [45], [46].

The recorded thermal response is subsequently evaluated using a lock-in amplifier. This involves a frequency-selective analysis of the temperature response with respect to the modulated excitation signal. This evaluation typically produces an amplitude image and a phase image. The amplitude image describes the intensity variation of the thermal response. The phase image contains information on the temporal shift between the excitation signal and the thermal response of the component [47], [48].

The phase image is of particular importance for non-destructive testing. Phase information is comparatively insensitive to non-uniform heating or varying surface properties. Regions with deviating thermal behavior can therefore indicate disturbances in heat flow [48].

A schematic representation of the experimental setup is shown in figure 5, while further details on the setup and the applied experimental parameters are provided in the corresponding table 5.

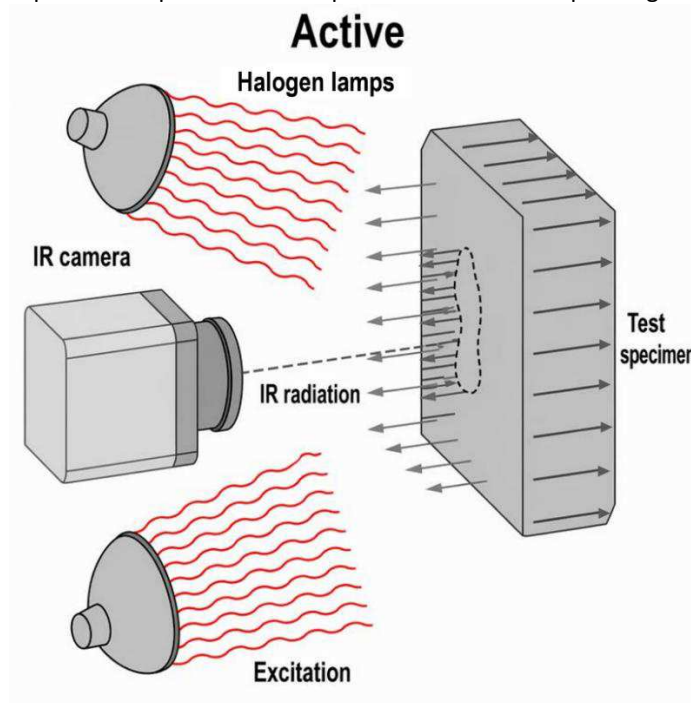


Figure 5: Schematic illustration of the Lock-in thermography system

Technical Parameter	Specification
Thermography system	edavis OTvis 10000
Excitation source	2 x Halogen lamps
Lamp power	2 × 1250 W per halogen lamp
Excitation mode	Periodically modulated thermal excitation
Modulation frequency range	0.006–794 Hz
Signal acquisition	Synchronous infrared acquisition

Table 5: Technical specifications and scanning parameters of the Lock-in thermography system

The results of the lock-in thermography investigations show that this method does not allow unambiguous detection of the actual bonding area in ultrasonically welded aluminum-copper dissimilar joints. Neither with existing anvil marks nor after their removal could the joining zone be reliably differentiated into bonded and non-bonded regions. Instead, the thermal response of the copper terminal to the heat input shows an approximately homogeneous temperature increase. Local temperature differences that could indicate variations in bonding between the aluminum stranded conductor and the copper terminal do not appear with sufficient contrast.

A major reason for this behavior is the high thermal conductivity of the materials involved, particularly that of the copper terminal. Copper distributes the heat introduced by the halogen lamps over large areas of the specimen geometry within a short period of time. As a result, local temperature gradients are strongly reduced. Thermal differences that could theoretically arise from bonded or non-bonded regions within the joining zone are therefore superimposed by the rapid lateral heat propagation. Consequently, the surface does not exhibit localized temperature contrasts but rather shows a largely uniform heating behavior.

Aluminum also exhibits high thermal conductivity. Therefore, the introduced heat is efficiently conducted not only within the copper terminal but also within the compacted aluminum stranded conductor. This is disadvantageous for thermographic detection of the bonding area, since the thermal response cannot be primarily attributed to the local condition of the interface. Instead, the measured temperature field is mainly governed by global heat propagation within the highly thermally conductive joining partners. Differences between metallurgically bonded and non-bonded regions are therefore attenuated and superimposed.

In addition, the bonding area to be detected is located within the joining zone and is not directly accessible at the excited or observed surface. Thus, a thermal contrast generated by local variations in bonding must first be transferred through the overlying material regions to the surface. This further complicates the unambiguous assignment of the measured temperature distribution to the actual bonding area.

Removal of the anvil marks also did not improve the detectability of the bonding area. Even after removing the surface imprint, the thermal response remained largely homogeneous. The measurement results indicate that surface effects are not the primary cause of the missing detectability of the bonding area. Instead, the dominant factor is the rapid heat distribution within the copper terminal.

Even with reduced terminal thickness, as shown in figure 6, no unambiguous visualization of the bonding area could be achieved. In principle, a lower material thickness can increase the thermal sensitivity to internal interfaces, as the distance between the joining zone and the surface is reduced. In the present case, however, this effect was not sufficient to generate an evaluable thermal contrast.

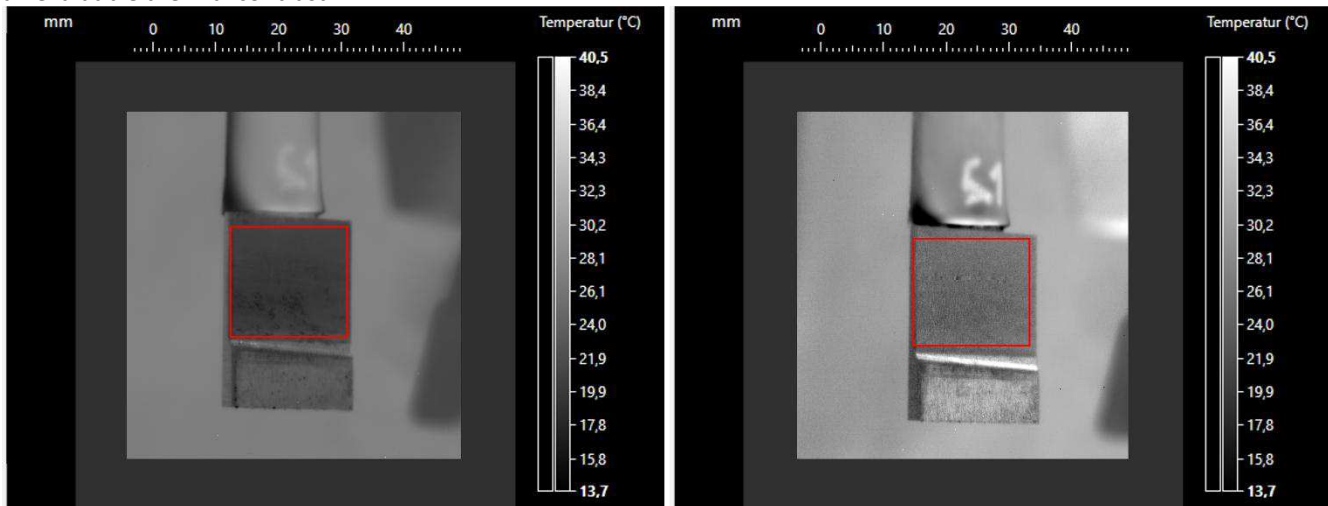


Figure 6: Time-dependent evolution of the thermal response of the copper connection due to external excitation

In summary, lock-in thermography does not provide reliable information on the actual bonding area under the boundary conditions investigated. The thermal response is predominantly determined by the rapid and spatially extensive heat propagation within the copper terminal and the aluminum stranded conductor. A clear distinction between bonded and non-bonded regions is therefore not possible. Consequently, lock-in thermography is not suitable either for detecting the actual bonding area or for assessing the joint quality of ultrasonically welded aluminum-copper dissimilar joints. Based on the results of the preliminary investigations, this method was therefore not considered for the subsequent detailed analyses.

3.2. Computed Tomography

The fundamental suitability of computed tomography for investigating ultrasonically welded aluminum stranded conductor-to-copper terminal connections results from its three-dimensional and non-destructive acquisition of the internal specimen structure. In contrast to purely surface-based testing methods, computed tomography enables a volumetric analysis of the welded joint [49], [50]. This allows the position of the aluminum strands, the deformation in the weld region, and the contact conditions between the aluminum conductor and the Cu-ETP terminal to be visualized with spatial resolution [43].

For the detection of the bonding area, the high material contrast between aluminum and copper is particularly relevant. Due to their different X-ray absorption characteristics, both materials can be distinguished in the tomographic dataset. This enables an analysis of the interface between the stranded conductor and the terminal. Regions with close contact or pronounced plastic deformation can be differentiated from areas containing gaps, voids, or insufficient contact. Thus, computed tomography can provide indications of the spatial extent of the actual bonding [51], [52].

Furthermore, computed tomography is suitable for evaluating geometrical influencing factors within the weld zone. These include the local compaction of the strands, the penetration depth into the terminal, the formation of voids, and the distribution of non-bonded regions. These characteristics are relevant for assessing the joint quality. The operating principle of computed tomography is based on the penetration of the specimen by X-ray radiation. When passing through the component, the radiation is attenuated to different extents depending on the material, density, atomic number, and penetration length. Materials with higher density absorb X-ray radiation more strongly and therefore result in lower intensity at the detector [51], [53].

The attenuation of X-ray radiation is described by the attenuation law. According to this law, the radiation intensity decreases exponentially with increasing penetration length and increasing attenuation coefficient. The attenuation coefficient depends on the material and on the energy of the applied X-ray radiation. The detected residual intensity therefore contains information about the internal material distribution along the respective beam path.

In addition to the previously discussed potential of CT analysis, several challenges remain regarding the non-destructive examination of ultrasonically welded Al-Cu joints. The main challenges are summarized as follows:

- **High attenuation contrast:** The substantially different X-ray attenuation of aluminum and copper complicates accurate reconstruction of the material interface.
- **Beam hardening:** Bright and dark streak artefacts may mask actual bonding defects or generate apparent defects.
- **Photon starvation:** Strong X-ray absorption within the copper reduces the photon flux reaching the detector and increases image noise.
- **Scattered radiation:** Superimposed scatter signals reduce edge sharpness and blur the Al-Cu interface.
- **Low contrast-to-noise ratio:** The high X-ray energy required to penetrate copper reduces the achievable contrast within the aluminum.
- **Metal artefacts:** Radial streak artefacts originating from copper edges may distort the geometry of the joining zone.
- **Limited spatial resolution:** Microscopic gaps and thin intermetallic phases may remain unresolved due to partial-volume effects.

During the CT scan, the specimen is rotated stepwise or continuously relative to the X-ray source and the detector. In this process, numerous two-dimensional X-ray projections are acquired from different viewing directions. Each projection represents the accumulated attenuation of the X-ray radiation along the respective penetration direction. The attenuated radiation then reaches a detector and is converted into digital grayscale information. The corresponding grayscale value is related to the X-ray attenuation of the material.

From the large number of projection images, a three-dimensional volume model of the specimen is reconstructed computationally. For this purpose, mathematical reconstruction algorithms are used to calculate the spatial distribution of local absorption from the different attenuation data. The reconstructed volume consists of individual volume elements. Differences in material composition, density, or geometry therefore led to different grayscale values in the CT dataset. Materials with high X-ray attenuation typically appear brighter, whereas regions with lower attenuation are displayed darker. This enables internal structures, interfaces, and geometrical features to be visualized. Defects such as pores, voids,

or shrinkage cavities exhibit different attenuation due to their lower material density and can therefore be identified within the reconstructed volume [54].

The evaluation focuses on both cross-sections through the weld knot and sectional views at the depth of the joining zone previously determined by scanning acoustic microscopy. The cross-sections of the poor welds from test series B shown in figure 7 reveal distinct structural irregularities. In accordance with SAE/USCAR38-2, the section was taken at a low point of the welded joint [34].

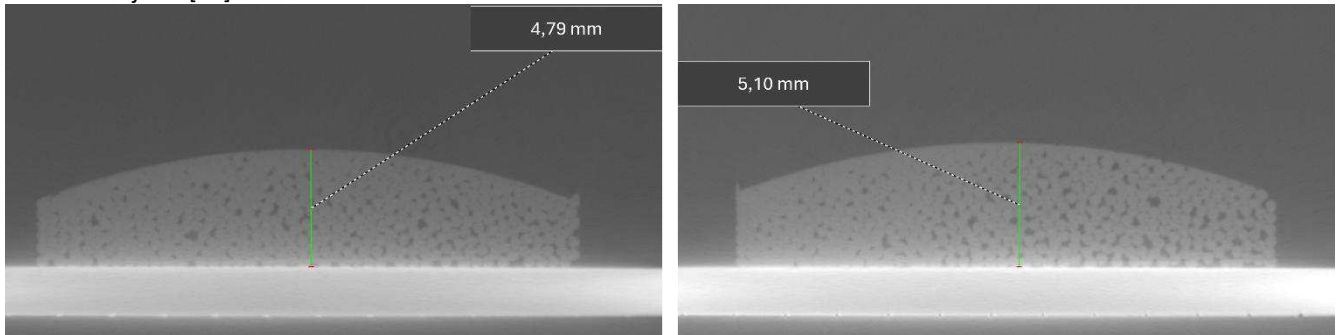


Figure 7: Strand compaction of the Test Series B

It can be observed that many individual strands were only slightly or insufficiently plastically deformed. In addition, defects and incompletely compacted regions occur across the entire weld. These characteristics indicate insufficient compaction of the strand bundle and suggest that both the bonding between the individual strands and the bonding to the copper terminal are inadequately formed. In comparison, the cross-sections of the good welds from test series A show a significantly more homogeneous structure, as shown in figure 8.

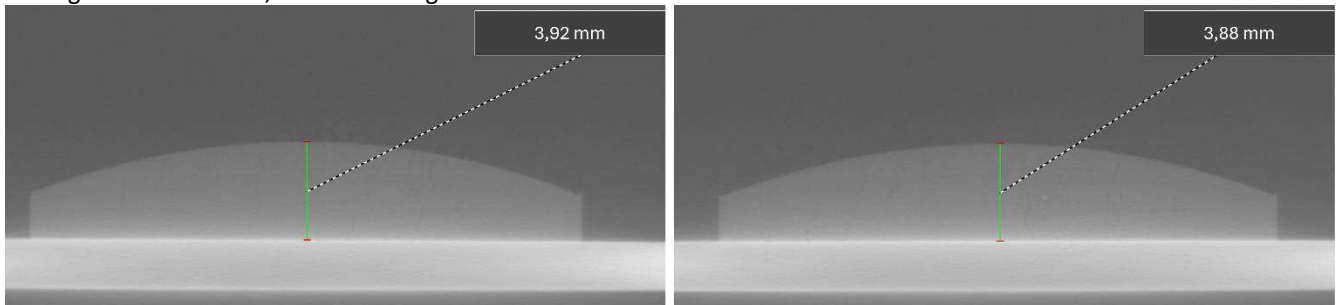


Figure 8: Strand compaction of the Test Series A

Undeformed individual strands or pronounced defects are not visible in the presented sections. The strands appear highly compacted and more uniformly integrated into the weld nugget. This indicates intensive plastic deformation during the welding process and good bonding between the individual strands.

The measured compaction height confirms this difference. While the good welds exhibit stronger compaction with values of approximately 3.88 mm to 3.92 mm, the poor welds show significantly higher values of approximately 4.79 mm to 5.10 mm. The lower compaction height of the good welds indicates a higher energy input during the welding process.

The sectional views within the joining zone show a large number of aluminum strands in the investigated section plane for both good and poor welds. This section was determined beforehand using scanning acoustic microscopy, as this method provides precise information regarding the depth at which metallurgical bonding can be detected. In this plane, CT enables an assessment of the spatial position and distribution of the strands within the copper terminal.

It becomes apparent that the section plane of the poor welds exhibits a more discontinuous structure. This is consistent with the previously determined lower degree of compaction and the greater compaction height. The sectional images at the corresponding depth are shown in figure 9.

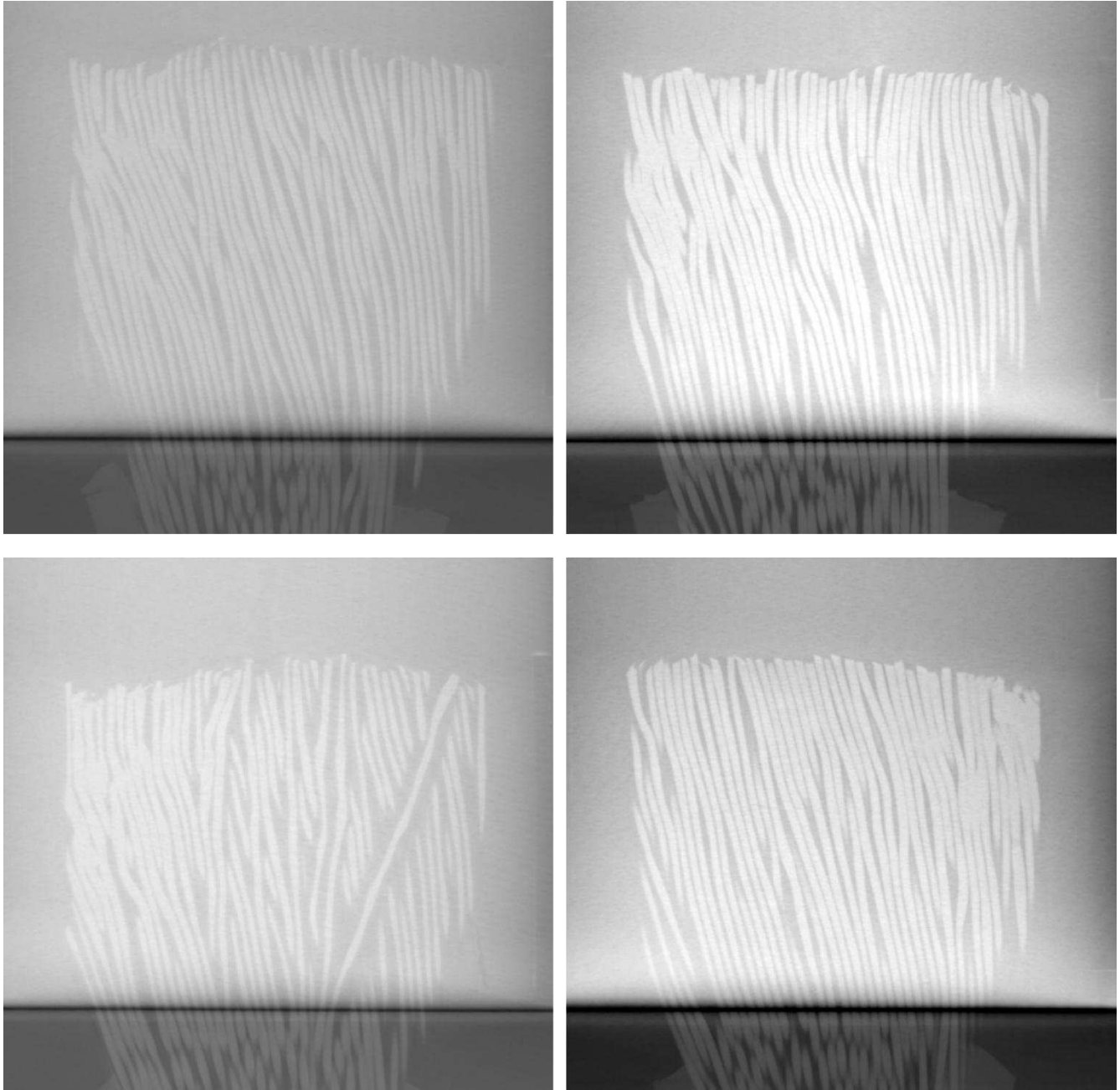


Figure 9: Sectional view of the bonding surface in Test Series B

For the good welds, a significantly more uniform and denser strand structure is visible, particularly in the central region of the joining zone. The corresponding cross-section in the bonding plane is shown in figure 10. This indicates improved compaction of the strand bundle and more favorable contact conditions between the aluminum stranded conductor and the copper terminal.

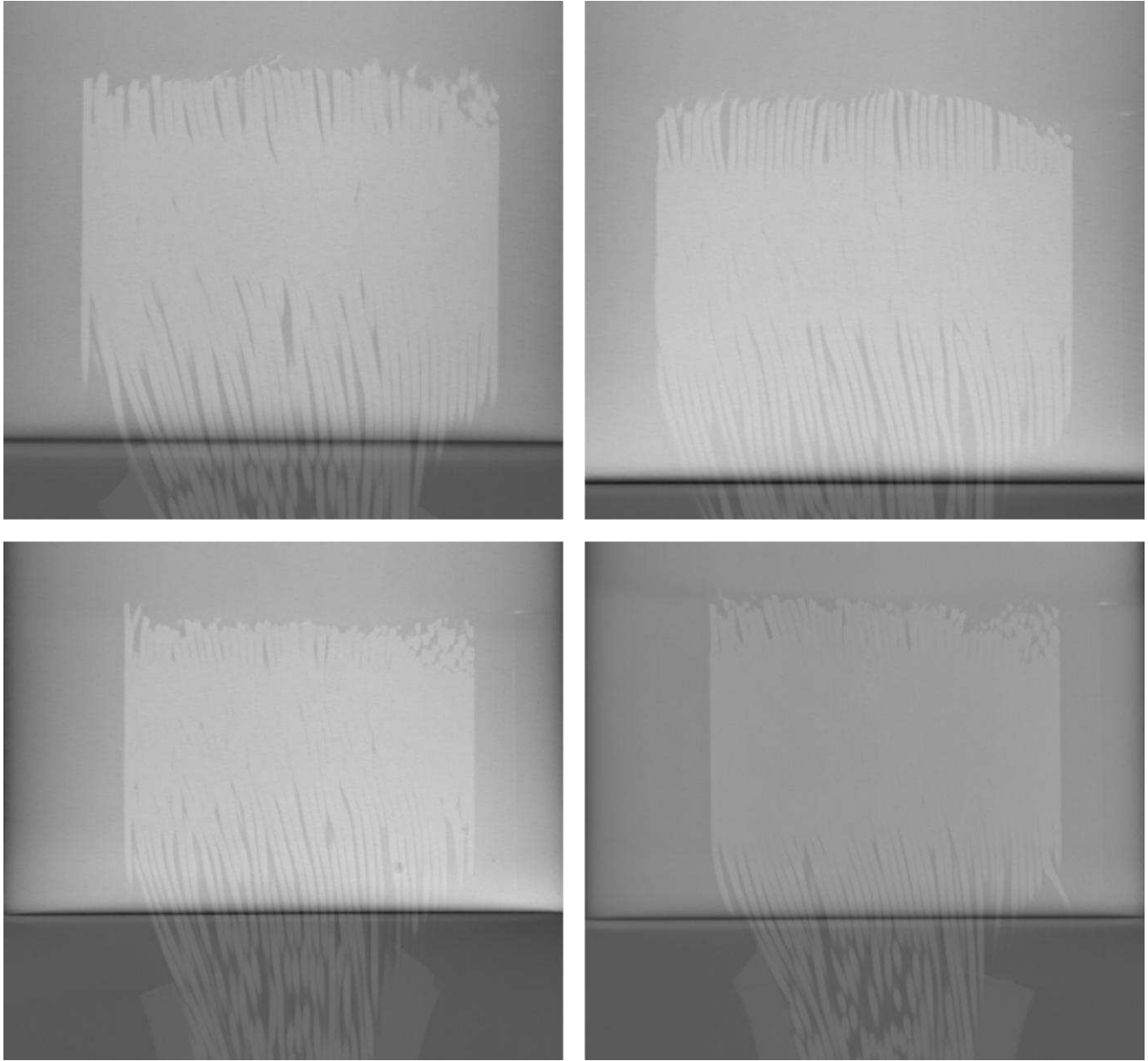


Figure 10: Sectional view of the bonding surface in Test Series A

The CT results therefore suggest that the good welds exhibit more pronounced compaction and a more homogeneous structure within the joining zone than the poor welds. However, the extent to which the regions visible in the CT data correspond to an actual metallurgical bond must be evaluated by comparison with the other non-destructive testing methods, particularly scanning acoustic microscopy.

3.3. Ultrasonic Testing

The fundamental suitability of ultrasonic testing methods for the analysis of ultrasonically welded aluminum-copper joints results from the interaction of mechanical waves with internal interfaces and material inhomogeneities. In ultrasonic testing, high-frequency sound waves are introduced into the specimen. Their propagation is influenced by the acoustic properties of the materials as well as by the quality of the interface between the aluminum stranded conductor and the Cu-ETP terminal [43], [55].

For the detection of the bonding area, the interface between the aluminum stranded conductor and the Cu-ETP terminal is particularly relevant. In well-bonded regions, improved transmission of acoustic energy across the interface is expected. In contrast, non-bonded or insufficiently bonded regions can cause reflections, scattering, or attenuation of the ultrasonic signal. These signal-based differences provide information about the local formation of the bonding area [56].

As already known, the actual bonding in ultrasonically welded aluminum stranded conductor-to-copper terminal connections is locally limited and irregularly distributed. Ultrasonic testing therefore offers the advantage that differences in the acoustic behavior of the interface can be visualized. Regions without an actual metallurgical bond exhibit different reflection behavior and consequently lead to changes in the ultrasonic signal. Thus, ultrasonic testing methods represent a suitable approach for non-destructively characterizing the bonding area and deriving indications of the quality of the welded joint [55], [57].

In addition to its potential for non-destructive bond evaluation, ultrasonic testing of Al-Cu joints is subject to several technical challenges, which are summarized below.

- **Acoustic impedance mismatch:** The substantial difference in acoustic impedance between aluminum and copper generates a strong reflection even at an intact interface.
- **Superposition of defect echoes:** Reflections from microscopic bonding defects may be masked by the dominant interface echo.
- **Intermetallic phases:** Variations in elastic properties and acoustic wave velocities can alter the ultrasonic response of the transition zone.
- **Microstructural scattering:** A microscopically rough and heterogeneous interface causes acoustic scattering and reduces the signal-to-noise ratio.
- **Phase distortion:** Irregular transition zones broaden the echo signals and impair accurate depth localization.
- **Acoustic refraction:** Differences in wave velocity cause refraction of the sound beam under oblique incidence.
- **Mode conversion:** Longitudinal waves may be partially converted into shear waves at the Al-Cu interface.
- **Limited defect localization:** Refraction, scattering, phase distortion, and mode conversion complicate the unambiguous assignment of measured echoes to the actual bonded area.

In ultrasonic testing, the acquired signals can be evaluated using different display modes. In general, a distinction is made between A-scan, B-scan, and C-scan representations. The A-scan displays the reflected ultrasonic signal at a single measurement point. In this representation, the signal amplitude is plotted as a function of time-of-flight. The time-of-flight provides information about the depth position of reflecting interfaces or defects, while the amplitude provides information about the intensity of the reflection. The B-scan is generated by arranging multiple A-scans along a defined scan line. This results in a two-dimensional cross-sectional representation of the specimen. In this representation, both the lateral position and the depth position of interfaces, inhomogeneities, or defects can be visualized. The B-scan is therefore particularly suitable for evaluating the internal structure along a defined section plane. In contrast, the C-scan represents a planar top-view image of a defined depth range or interface within the specimen. For this purpose, the probe is moved over the component surface in a raster pattern. At each measurement point, a selected signal parameter, such as amplitude or time of flight, is displayed with spatial resolution. This produces a two-dimensional map of the investigated region [58], [59], [60]. For the detection of the bonding area in ultrasonically welded aluminum stranded conductor-to-copper terminal connections, the C-scan is of particular importance. Figure 11 illustrates the different section planes used in ultrasonic testing as well as the applied scanning procedure.

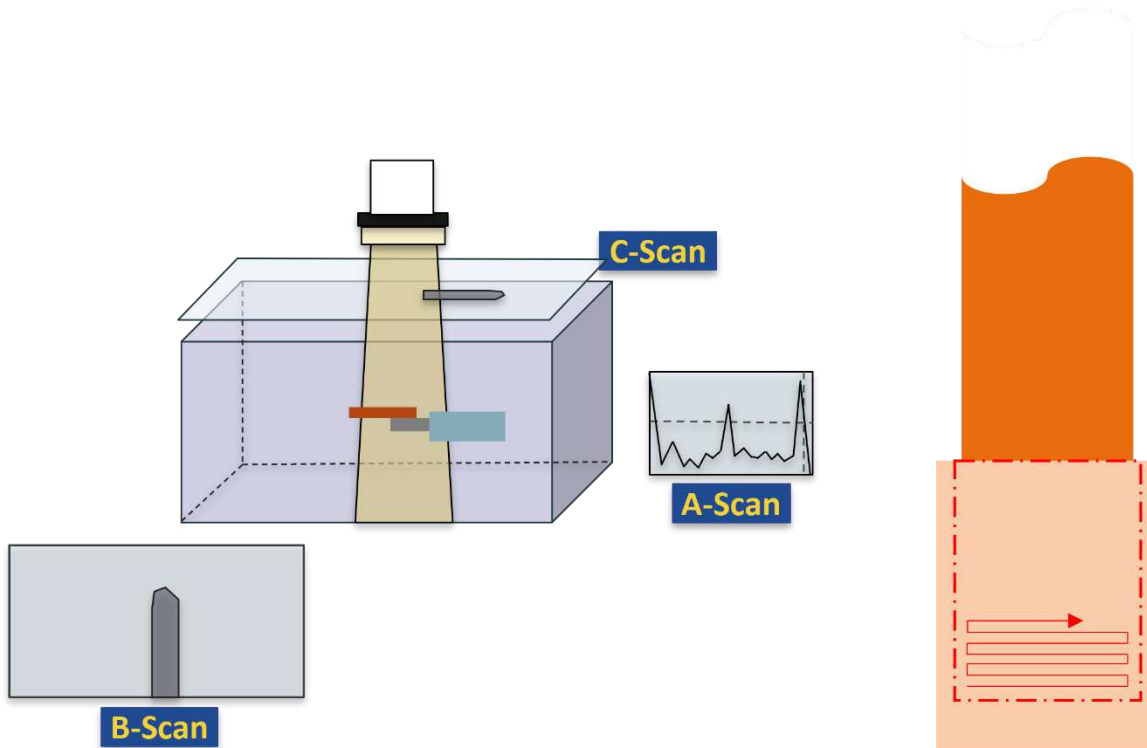


Figure 11: Cross-sectional levels and scanning patterns in ultrasonic testing

For the ultrasonic-based detection of the actual bonding area, two testing methods are considered in the following sections: laser ultrasonic testing and scanning acoustic microscopy. Both methods are investigated with regard to their operating principles and their applicability to ultrasonically welded aluminum stranded conductor-to-copper terminal connections. First, the functional principle of each method is described. Subsequently, the experimental results obtained from the investigations are presented and evaluated.

3.3.1. Laser Ultrasonic Testing

Laser ultrasonic testing is a non-destructive and contactless ultrasonic testing method. It is based on the laser-induced generation and optical detection of ultrasonic waves within the specimen. This enables defects and internal features to be investigated without direct mechanical contact with the component surface [57], [61].

To generate ultrasonic waves, a short-pulsed or continuously intensity-modulated laser beam is directed onto the component surface. Locally introduced energy causes rapid thermal expansion in the near-surface region. This thermoelastic expansion generates mechanical stress waves, which propagate through the material as ultrasonic waves. At higher laser energies, local surface ablation may additionally occur, which can also excite ultrasonic waves. The generated ultrasonic waves propagate through the component and are reflected, scattered, or attenuated at interfaces, defects, or material transitions. Regions with different acoustic impedances, such as transitions between aluminum and copper or non-bonded interfaces, influence the wave propagation behavior. As a result, measurable changes in time of flight, amplitude, and signal shape occur. The basic principle of laser ultrasonic testing is schematically illustrated in the following figure 12 [61], [62].

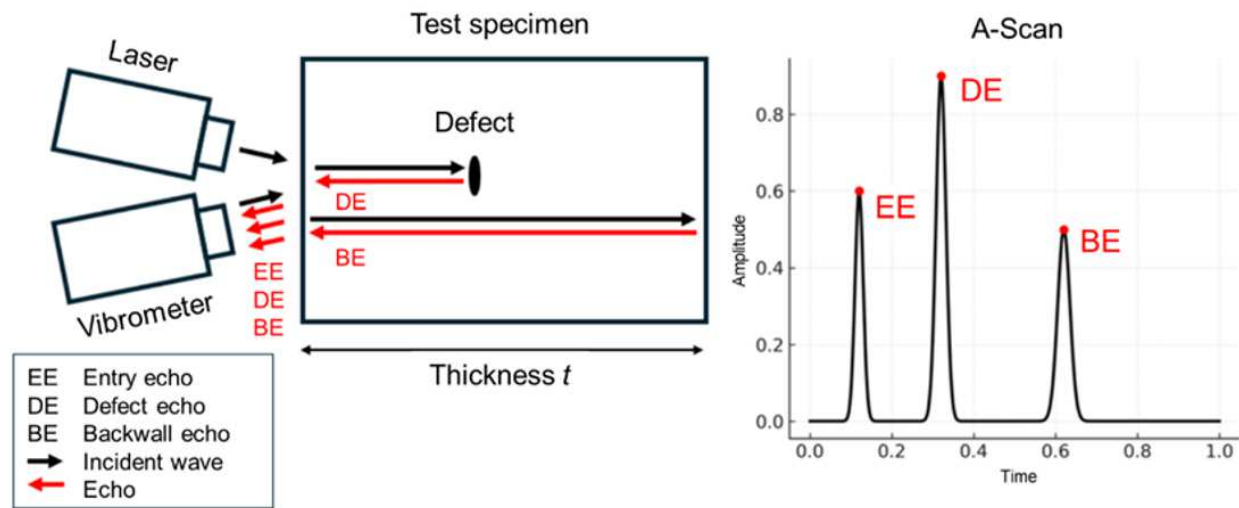


Figure 12: Functional principle of laser ultrasonic testing

The detection of the ultrasonic signals is also performed contactless. For this purpose, an interferometric measurement system is commonly used, which detects very small surface vibrations of the component. These vibrations are generated by reflected or returning ultrasonic waves. Based on the detected signals, conclusions can be drawn regarding the internal structure of the specimen and possible discontinuities within the joining zone [57], [63], [64].

The results of the laser ultrasonic testing show that the detectability of the bonding area in ultrasonically welded aluminum-copper dissimilar joints is significantly influenced by the surface condition of the copper terminal. The investigations on different terminal configurations, shown in figure 13, demonstrate that no reliable visualization of the bonding area within the joining zone is possible for specimens with existing or only slightly reduced anvil marks. In these cases, the method did not provide a clear differentiation between metallurgically bonded and non-bonded regions.

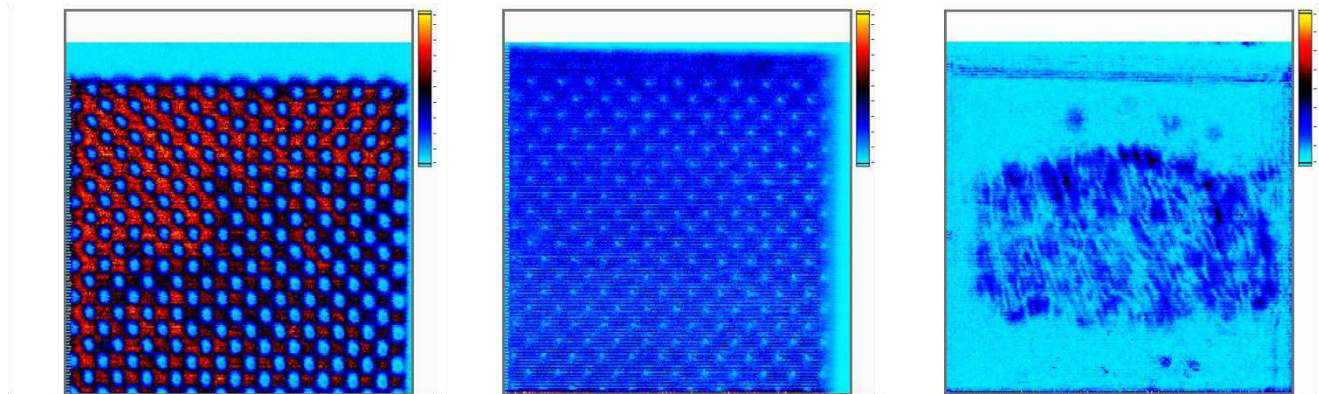


Figure 13: Detected bonding surface with original(left), reduced(middle) and no (right) anvil residues

A key reason for this behavior is the surface modification on the terminal induced by the welding process. The anvil marks result in a locally altered surface topography, which affects both the laser-induced generation of ultrasound and the subsequent wave propagation. Consequently, the incident laser pulse does not interact with a homogeneous surface but is locally deflected or disturbed by the imprinted structure of the anvil marks.

Consequently, the ultrasonic wave generated at the terminal surface does not propagate uniformly into the component. This leads to erroneous or superimposed detection of the echo signal, preventing an unambiguous evaluation of the actual interface information within the joining zone. The resulting artefact pattern is shown in figure 14.

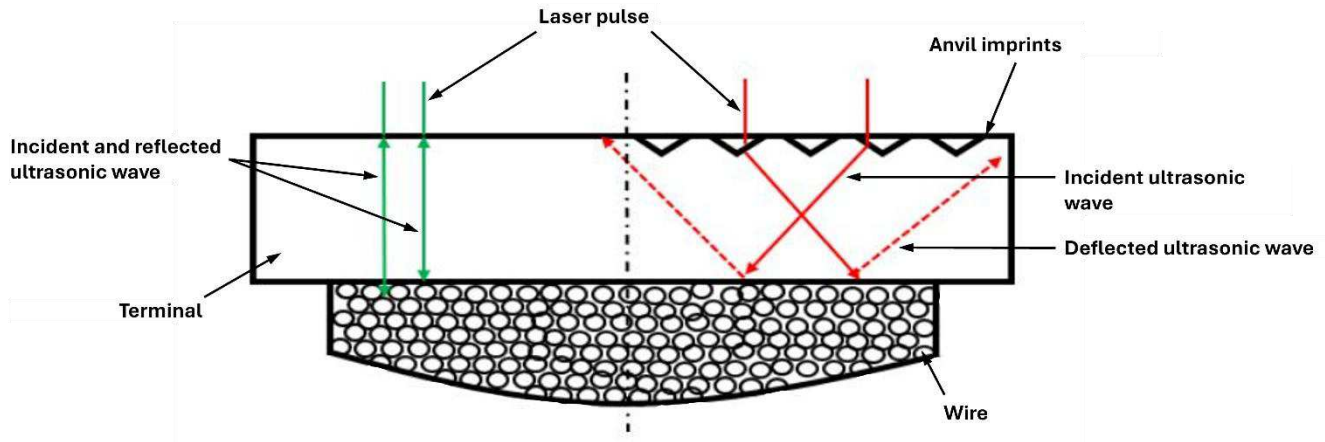


Figure 14: Schematic illustration of ultrasonic deflection with optimum (left) and disturbed (right) wave propagation

Only after complete removal of the anvil marks was it possible to detect the actual bonding area between the copper terminal and the aluminum stranded conductor. The generated C-scan provides a visual representation of the locally bonded regions within the joining zone. In this representation, the metallurgically bonded areas appear darker. By scanning the entire weld region, a clear image of the spatial extent of the bond is obtained. Thus, laser ultrasonic testing generally demonstrates the potential to visualize the actual bonding area in aluminum-copper dissimilar joints in a non-destructive manner.

However, the practical applicability of this method is significantly limited. Reliable detection was only possible after complete removal of the anvil marks. This additional preparation step does not correspond to conditions suitable for series production, since the welded joint is normally assessed after the joining process with the tool imprint still present. Furthermore, mechanical removal of the anvil marks may affect the joining zone. There is a risk that near-surface micro-welds or locally bonded regions are damaged or removed during machining. As a result, the actual bonding area may be altered or reduced.

In summary, laser ultrasonic testing enables detection of the bonding area under idealized surface conditions. However, the measurement results also show that the anvil marks generated during the welding process significantly impair the signal quality and prevent reliable evaluation. Since the required removal of the anvil marks is neither representative of series-production conditions nor ensures an unchanged assessment of the original joint, laser ultrasonic testing is not considered for the subsequent detailed investigations.

3.3.2. Scanning Acoustic Microscopy

Scanning acoustic microscopy is a non-destructive testing method for the high-resolution investigation of internal interfaces and near-surface component regions. The method is based on the emission of high-frequency ultrasonic pulses into the specimen. The sound waves propagate through the material and are reflected at interfaces, defects, or regions with altered acoustic properties [59], [60].

The operating principle is based on differences in acoustic impedance, which is determined by the density and sound velocity of the respective material. When ultrasonic waves encounter a transition between two media, part of the acoustic energy is reflected, while another part is transmitted. Non-bonded regions, voids, or interfaces cause strong reflections, whereas metallurgically bonded regions enable improved transmission of the ultrasonic waves [60], [65].

In scanning acoustic microscopy, the probe is moved over the component surface in a raster pattern. Water is typically used as a coupling medium to ensure low-loss transmission of the ultrasonic waves between the probe and the component. At each measurement point, the reflected ultrasonic signal is recorded and evaluated with respect to time of flight and amplitude. The time of flight provides information about the depth position of reflecting interfaces, while the amplitude describes the intensity of the reflection and allows conclusions to be drawn regarding the acoustic contrast within the investigated region [66], [67].

Based on the recorded signals, imaging representations can be generated. C-scans enable a planar visualization of defined depth regions within the specimen. This allows bonded and non-bonded regions within the joining zone to be distinguished with spatial resolution [67].

The preliminary investigations using test series P showed that scanning acoustic microscopy enables clear detection of the bonding area, independent of the investigated terminal geometry. Based on these results, the method was selected for the subsequent investigations of test series A and B. Therefore, the following section focuses on the evaluation of the C-scans of the good and poor welds.

The presented C-scans show distinct differences in the formation of the detected bonding area. For the good welds, shown in figure 15, a larger and more continuous bonding area is visible within the red-marked evaluation region. The bonded regions extend over a larger portion of the joining zone and exhibit a more pronounced planar distribution. This indicates that several strand regions are metallurgically bonded to the copper terminal and that bond formation occurs over almost the entire working area of the sonotrode.

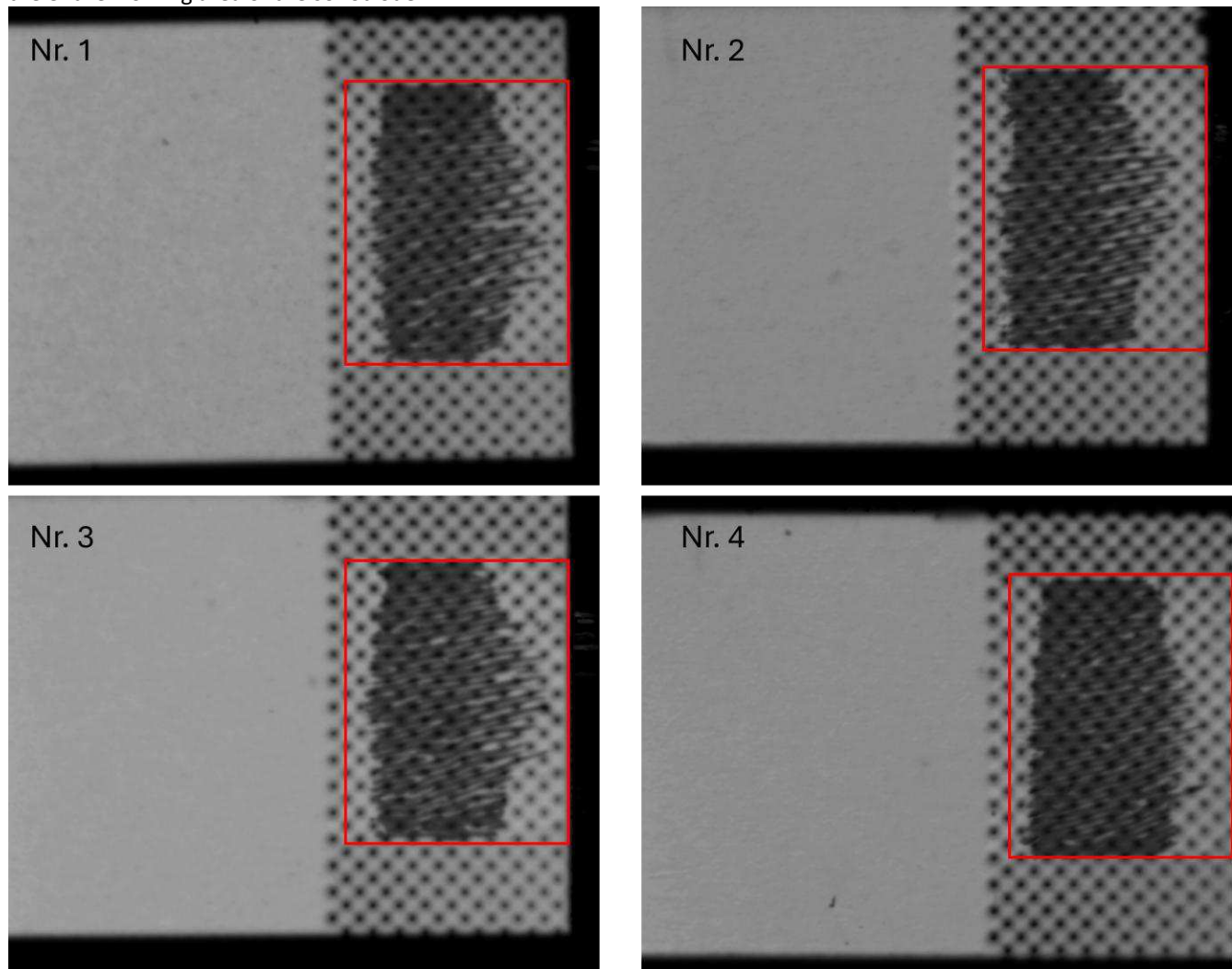


Figure 15: Detected bonding area in test series A

The C-scans of the good welds show a reproducible formation of the bonding area. The investigated specimens exhibit approximately the same area characteristics and distribution of the bonded regions. This indicates that stable and repeatable bond formation is achieved when optimized welding parameters are applied.

In contrast, the C-scans of the poor welds show a significantly smaller and more irregular bonding area. The results of the C-scans generated for test series B are shown in figure 16. In the specimens of test series B, only individual strand regions can be identified as metallurgically bonded. The bonding does not extend over the entire working width of the sonotrode but is locally limited and spatially inhomogeneous. A continuous or uniformly formed bonding area is not visible.

The irregular distribution of the bonded regions demonstrates that non-optimized welding parameters do not result in a reproducible, planar bond between the aluminum stranded conductor and the copper terminal. Instead, the bonding area forms individually for each weld. Based on the presented C-scans, no preferred location within the joining zone can be clearly

identified where metallurgically bonded regions occur more frequently. This indicates that local bond formation is strongly influenced by the random arrangement of the individual strands, the local contact conditions, and the local energy input during the welding process.

The results demonstrate that scanning acoustic microscopy is highly suitable for the spatially resolved evaluation of the actual bonding area. Using C-scan imaging, bonded and non-bonded regions within the joining zone can be visually distinguished. In particular, the comparison between good and poor welds shows that differences in joint quality are directly reflected in the size and distribution of the detected bonding area.

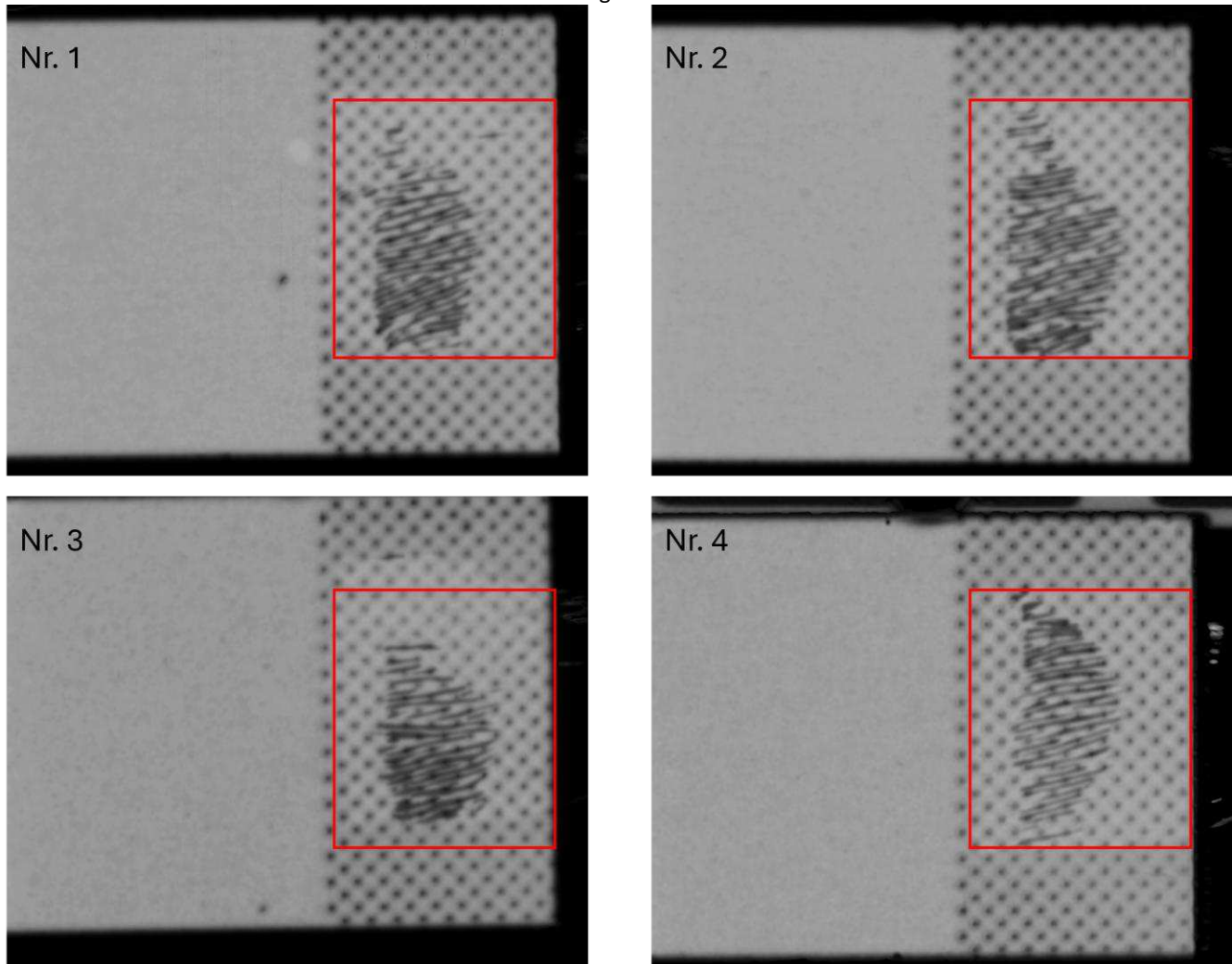


Figure 16: Detected bonding area in test series B

3.4. Correlation between bonding area and joint quality

The final correlation between the non-destructively detected bonding area and the destructively determined shear tensile force is a central step in assessing the informative value of the applied testing methods. The bonding area describes the region within the joining zone between the aluminum stranded conductor and the copper terminal with material locking properties. It therefore represents a quality characteristic that may allow conclusions to be drawn regarding the electrical and mechanical performance of the joint. However, to use this characteristic as a reliable criterion for assessing joint quality, its relationship with an established mechanical reference value must be demonstrated.

The shear tensile force is determined in the final investigation step by means of destructive shear tensile testing. It serves as a reference value for the mechanical strength of the joint. By comparing this value with the previously non-destructively determined bonding area, it can be evaluated to what extent a larger metallurgically bonded area within the joining zone

leads to higher shear tensile forces. A positive correlation between these two parameters would indicate that the detected bonding area provides not only geometrical information about the joining zone but also has direct relevance for the mechanical joint quality.

This correlation is particularly important because non-destructive testing methods are only suitable for quality-related assessment if their results can be linked to the actual mechanical behavior of the joint. Without this validation, the bonding area could be detected, but its significance for the resulting joint quality would remain unclear. Only by comparing it with the shear tensile force can it be assessed whether the bonding area is a reliable quality indicator for ultrasonically welded aluminum-copper dissimilar joints.

A demonstrable increase in shear tensile force with increasing bonding area confirms that a larger welded area contributes to higher mechanical load-bearing capacity of the joint. Consequently, the non-destructively determined bonding area can be used as a suitable characteristic for evaluating joint quality. At the same time, this provides the basis for the future implementation of non-destructive testing methods in near-series quality assessment and for reducing the extent of destructive testing.

3.4.1. Shear tensile test

The shear tensile test is used for the mechanical evaluation of joined connections [34]. In this work, it is applied as a destructive reference method to determine the maximum transferable force of ultrasonically welded aluminum-copper dissimilar joints. In a conventional tensile test, the material behavior of a defined specimen is characterized under uniaxial tensile loading, with the focus primarily on the mechanical properties of the base material [68]. In contrast, the shear tensile test focuses on the mechanical load-bearing capacity of the joining zone. Thus, the base material itself is not the primary subject of evaluation; rather, the maximum load capacity of the produced joint is assessed. The objective is to determine the force at which the connection between the aluminum stranded conductor and the copper terminal fails [69].

For this purpose, the copper terminal and the aluminum stranded conductor are fixed in such a way that the applied tensile force induces a shear load in the region of the joining zone. Subsequently, the movable crosshead of the testing machine is displaced at a defined testing speed. As a result, the joint is continuously loaded until failure occurs either in the welded joint or in the adjacent base material.

The test setup used for the shear tensile test is schematically shown in figure 17.

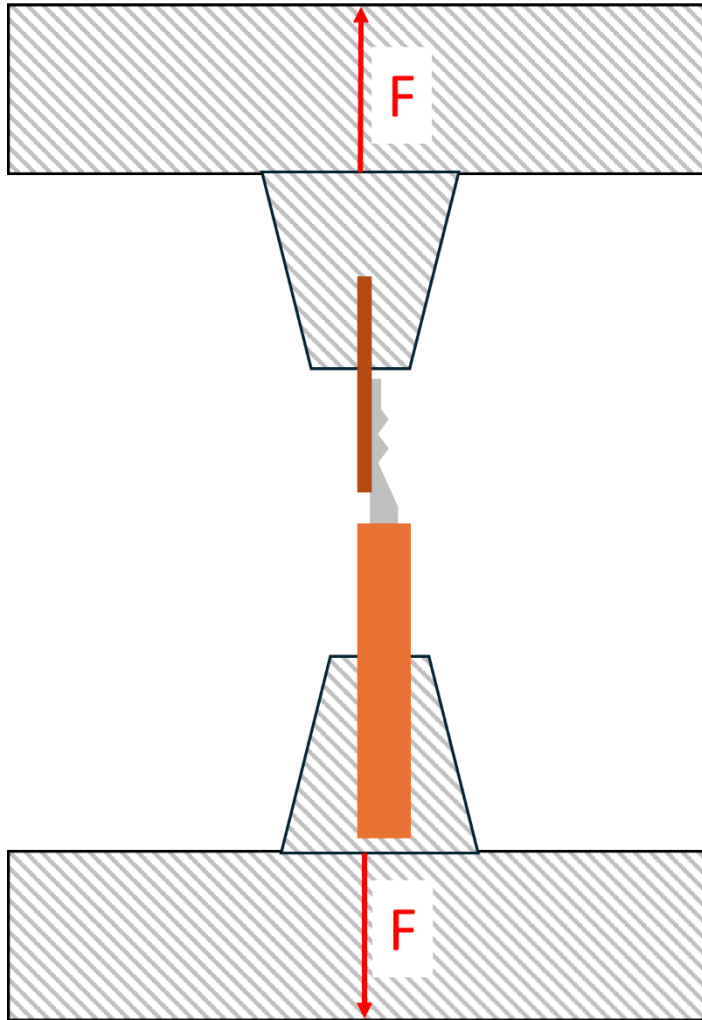


Figure 17: Schematic illustration of the tensile shear test

For the present investigation, the shear tensile test is of central importance, as it serves as a destructive reference test for assessing the joint quality. The bonding area previously determined using non-destructive testing methods describes the detected welded region within the joining zone. To evaluate whether this area is suitable as a quality-relevant characteristic, it must be correlated with a mechanical test parameter. The shear tensile force represents a suitable reference value for this purpose, as it directly describes the mechanical load-bearing capacity of the aluminum-copper joint.

By comparing the bonding area with the shear tensile force, it can be evaluated to what extent a larger metallurgically bonded area leads to higher mechanical load-bearing capacity. A positive correlation between both parameters indicates that the detected bonding area has a direct influence on the joint strength.

For the mechanical evaluation of the ultrasonically welded aluminum-copper dissimilar joints, shear tensile tests were performed. A Zwick universal testing machine was used as the test system. The aluminum stranded conductor and the copper terminal were clamped using wedge-screw grips, which are typically used for tensile testing. The testing machine has a maximum load range of ± 250 kN and therefore enables sufficiently accurate acquisition of the shear tensile forces occurring during the test.

Uniform testing conditions were defined for the experimental procedure. The test speed was set to 10 mm/min. As the termination criterion, a force cut-off threshold of 80% after force drop was specified. Accordingly, the test was terminated after the maximum force had been exceeded and a subsequent significant decrease in force had occurred. This enabled the maximum transferable shear tensile force to be determined for each specimen.

The results shown in figure 18 present the maximum shear tensile forces achieved by the specimens from test series A and B. The shear tensile force represents the central mechanical characteristic for evaluating the joint quality.

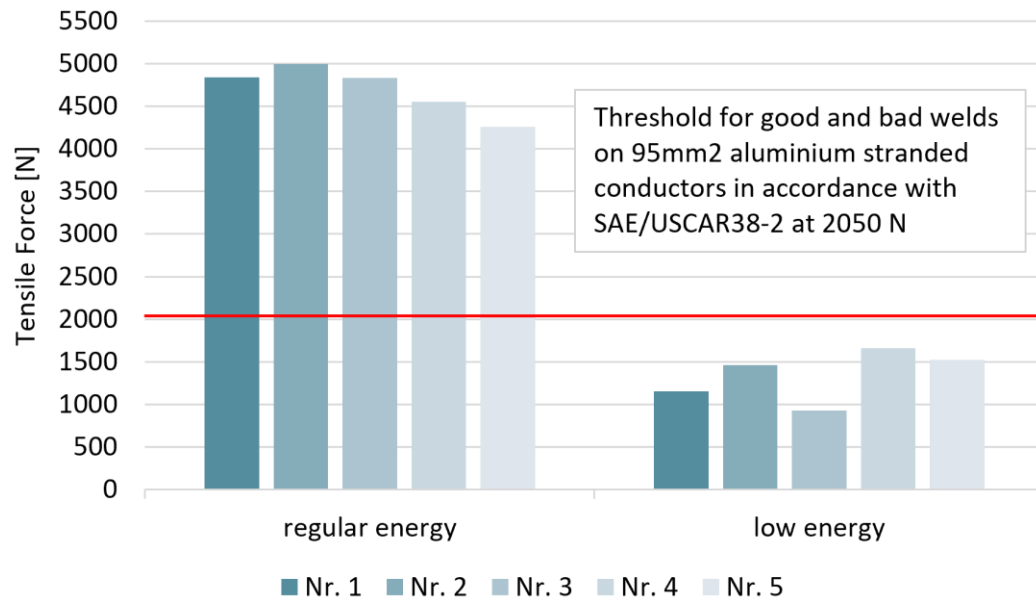


Figure 18: Results of the tensile shear test

The results of the shear tensile tests show a clear differentiation between the specimens classified as good and poor welds. As shown in figure 18, all good welds exceed the minimum tensile force of 2050 N required by SAE/USCAR38-2 for aluminum stranded conductors with a nominal cross-section of 95 mm². In contrast, all poor welds fall below this threshold. Thus, the shear tensile test confirms the mechanical separation of the two test series. The good welds exhibit sufficient mechanical load-bearing capacity and meet the required minimum strength. The poor welds, however, do not reach the required tensile force and must therefore be evaluated as mechanically insufficient. The clear separation of the maximum shear tensile forces demonstrates that the selected welding parameters lead to reproducibly different joint qualities.

3.4.2. Correlation of non-destructive testing methods

The comparison of the applied non-destructive testing methods shows that not all methods are equally suitable for detecting the actual bonding area in ultrasonically welded aluminum-copper dissimilar joints. The thermographic methods did not enable clear identification of the bonding area, as the thermal response was predominantly governed by the high thermal conductivity of the copper terminal. Laser ultrasonic testing generally showed potential for detecting bonded regions; however, evaluation was only possible after mechanical removal of the anvil marks. Since this additional preparation step does not correspond to near-series testing conditions, the method is only of limited suitability for process-oriented assessment of joint quality.

Therefore, only computed tomography and scanning acoustic microscopy were considered for direct comparison of the detected bonding areas. The results shown in figure 19 and figure 20 reveal clear differences between both methods for both good and poor welds. While scanning acoustic microscopy provides information on the acoustic behavior of the interface through the evaluation of echo signals, computed tomography primarily visualizes the geometrical position of the aluminum strands in a defined cross-sectional plane.

The most pronounced difference between the two methods is observed for the poor welds. In the CT cross-sectional images, the potentially bonded area appears significantly larger than the metallurgical bond detected by scanning acoustic microscopy. This is because computed tomography only indicates whether aluminum strands are present in the investigation section plane. However, a reliable distinction between purely mechanical contact, plastic embedding of the aluminum strands into the copper terminal, and actual welding cannot be derived unambiguously. Consequently, there is a risk that strand regions visible in the CT data may be incorrectly interpreted as bonded areas.

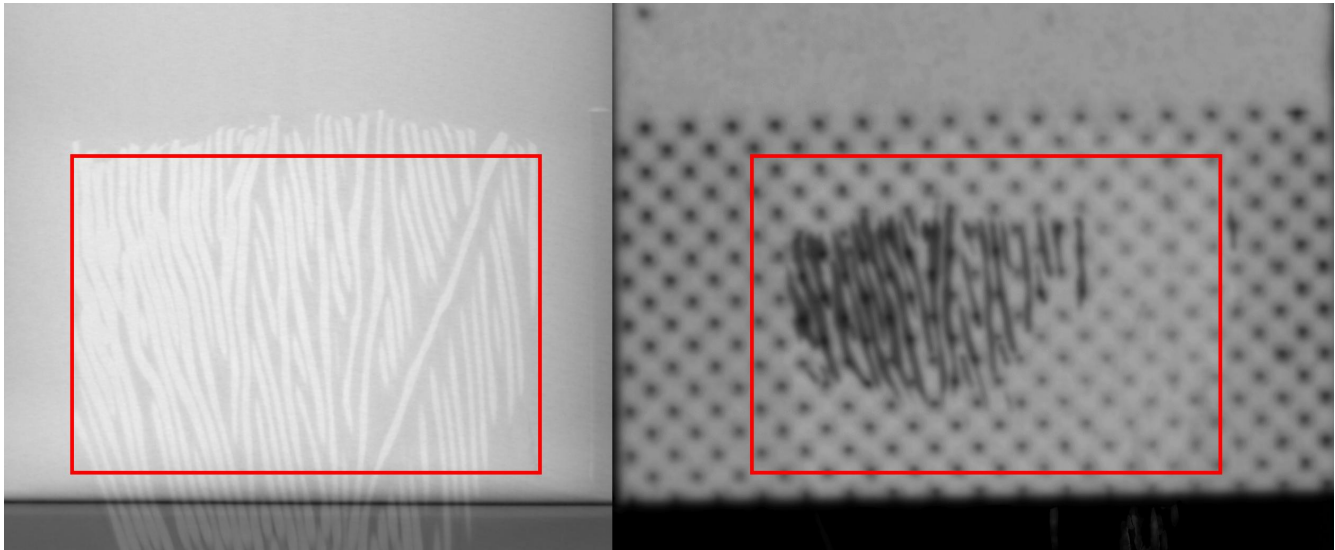


Figure 19: Comparison of the bonding area detected using CT (left) and SAM (right) for bad welds

In contrast, scanning acoustic microscopy shows that significantly fewer regions are bonded in the poor welds than initially suggested by the CT representation. The detected bonding area is locally limited and irregularly distributed. This demonstrates that the presence of aluminum strands within the joining zone cannot automatically be equated with a metallurgical bond. Particularly in the case of insufficient process control, strands may be geometrically located within the joining zone without forming an adequate metallurgical bond to the terminal.

In the comparison of the good welds (figure 20), however, better agreement between the two methods is observed. Both the C-scans obtained by scanning acoustic microscopy and the CT cross-sectional images show a clearly pronounced joint in the central region of the joining zone across the width of the sonotrode. Scanning acoustic microscopy confirms a large-area metallurgical bond, while computed tomography indicates a homogeneous strand distribution and strong compaction in the corresponding region. This suggests that, under optimized welding parameters, both good geometrical compaction and an actual metallurgical bond are formed.

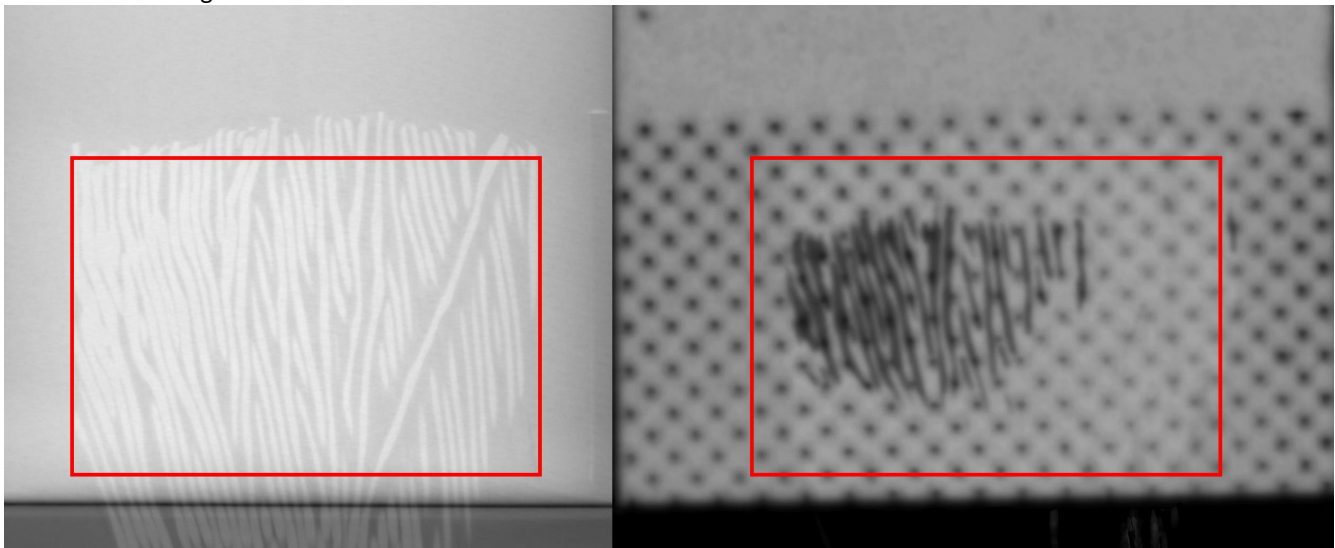


Figure 20: Comparison of the bonding area detected using CT (left) and SAM (right) for good welds

In summary, the comparison shows that computed tomography provides valuable information on the internal structure, the position of the strands, and the compaction state of the welded joint. However, the method is only suitable to a limited extent for the unambiguous detection of the actual bonding area, as it does not provide direct evidence of metallurgical bonding between the aluminum stranded conductor and the copper terminal. In contrast, scanning acoustic microscopy is

significantly better suited for identifying metallurgically bonded regions within the joining zone. It therefore provides a more reliable basis for evaluating the actual bonding area and assessing the joint quality.

3.4.3. Correlation between non-destructive and destructive testing methods

For the correlation between the detected bonding area and the mechanical load-bearing capacity of the welded joint, scanning acoustic microscopy proves to be particularly suitable. Through spatially resolved acquisition of the echo signals, this method enables a detailed visualization of the bonded regions within the joining zone. In particular, the generated C-scans provide visual feedback on the regions in which a metallurgical bond between the aluminum stranded conductor and the copper terminal is present.

However, a quantitative determination of the bonded area could not be performed within the scope of this investigation, as the applied testing system does not provide automated grayscale analysis for calculating the bonding area. Nevertheless, the C-scans, in combination with the maximum shear tensile forces, enable a qualitative assessment of the bond quality. On this basis, a correlation can be established between the visually detected bonding area and the mechanical load-bearing capacity of the joint.

As shown by the presented C-scans, the bonding areas of the good and poor welds differ significantly. The good welds exhibit a larger and more continuously bonded area within the joining zone. In addition, the specimens show an approximately comparable distribution and extent of the bonded regions, indicating reproducible bond formation when optimized welding parameters are applied. In contrast, the poor welds show only locally limited and irregularly distributed bonded regions. A planar bond extending across the entire working width of the sonotrode is not present.

These differences are directly reflected in the results of the shear tensile tests. The good welds achieve significantly higher maximum shear tensile forces, ranging from approximately 4250 N to 5000 N, and therefore exceed the threshold value of 2050 N specified by SAE/USCAR38-2 for aluminum stranded conductors with a nominal cross-section of 95 mm². In contrast, the poor welds remain clearly below this threshold and achieve maximum shear tensile forces of only approximately 900 N to 1600 N. Thus, the same trend is observed in both the mechanical testing results and the scanning acoustic microscopy evaluation.

The comparison of the results therefore confirms a clear relationship between the size or extent of the bonding area and the mechanical load-bearing capacity of the welded joint. A larger and more continuous bonding area leads to higher shear tensile forces, whereas a small and irregular bonding area is associated with reduced mechanical strength. This demonstrates that the actual metallurgical bond within the joining zone makes a decisive contribution to the load-bearing capacity of the ultrasonically welded aluminum-copper dissimilar joint.

The relationship identified in the present study between the extent of the bonded area and the maximum shear tensile force is consistent with findings reported in the relevant scientific literature. Previous studies have demonstrated that, within an appropriate process window, a larger bonded area is associated with a higher mechanical load-bearing capacity of ultrasonically welded Al-Cu joints. Furthermore, the literature describes a direct relationship between the applied welding energy and the resulting bonded area. Under otherwise constant welding conditions, an increase in energy input within the suitable process window promotes the formation of a larger bonded area and, consequently, enhances the mechanical strength of the joint. The present C-scan and shear tensile test results confirm these relationships, as joints exhibiting larger and more continuous bonded regions also achieved higher maximum shear tensile forces. Accordingly, the present findings are consistent with the current state of research and confirm the bonded area as a quality-relevant characteristic of ultrasonically welded Al-Cu joints [14], [16].

The established correlation shows that the bonding area detected by scanning acoustic microscopy represents a suitable testing criterion for assessing joint quality.

4. Summary

In the present study, the suitability of non-destructive testing methods for detecting the bonding area within the joining zone of ultrasonically welded aluminum-copper dissimilar joints was investigated. Based on the detected bonding area, it was further evaluated whether an assessment of the joint quality is possible. The welds of the test specimens were produced using a previously validated parameter set to ensure reproducible joint conditions.

In the first step, five non-destructive testing methods were analyzed in preliminary investigations using test series P. The results showed that neither lock-in thermography nor laser thermography provides reliable information regarding the bonding area. The main reason for this is the high thermal conductivity of the copper terminals. The heat introduced by the

laser or halogen lamp spreads very rapidly throughout the entire terminal, resulting only in an approximately homogeneous temperature distribution. Consequently, local differences within the joining zone cannot be resolved with sufficient accuracy. Therefore, the thermographic methods were not considered further in the subsequent investigations.

Using laser ultrasonic testing, the bonding area could generally be detected. However, this was only possible under the condition that the surface marks generated by the anvil on the terminals had been removed beforehand. Since this preparation step does not correspond to near-series testing conditions, the method was excluded from the subsequent detailed investigations. Consequently, test series A and B, which specifically included good and poor welds, were examined exclusively by scanning acoustic microscopy and computed tomography.

The CT analysis does not allow a direct statement as to whether a metallurgical bond is present between the aluminum stranded conductor and the copper terminal. Instead, it primarily provides information on whether aluminum strands are present in the investigated cross-sectional plane. Nevertheless, in combination with the degree of compaction and the compaction height, an assessment of the joint quality can be made. In contrast, scanning acoustic microscopy proved to be the most suitable method for detecting the bonding area. It provides a clear representation of the welded regions within the joining zone and thus enables a direct evaluation of the actual bonding.

Furthermore, a correlation between the bonding area determined by scanning acoustic microscopy and the shear tensile force was demonstrated. With increasing bonding area, the achieved shear tensile force also increases. This relationship confirms that the detected bonding area can be used as a suitable characteristic for assessing the joint quality of ultrasonically welded aluminum-copper dissimilar joints.

5. Conclusion

Based on the investigations conducted, several key conclusions can be drawn. The detection of the actual bonding area in ultrasonically welded aluminum-copper dissimilar joints is generally possible using non-destructive testing methods. The most informative results were obtained with ultrasonic-based testing methods. These methods enable a differentiated characterization of the joining zone and allow conclusions to be drawn regarding the spatial extent of the bond between the aluminum conductor and the copper terminal.

Suitable quality criteria can be derived from the non-destructively determined bonding areas. The bonding area represents a relevant characteristic for assessing joint quality. Larger and more homogeneously distributed bonded regions can be interpreted as an indication of improved mechanical joint quality. At the same time, the results show that the bonding area should not be considered in isolation. For a reliable quality assessment, it is necessary to correlate the bonding area with mechanical properties, particularly the shear tensile force.

Direct integration of the testing methods investigated into series production is currently only possible to a limited extent. The main reasons for this are the required testing effort, the inspection time, and the necessary data processing and interpretation of the measurement results. Therefore, the methods are particularly suitable for evaluating new component geometries, investigating modified material combinations, and optimizing process parameters. In this context, they can make a significant contribution to process development and to the validation of ultrasonically welded joints.

The non-destructive testing methods cannot fully replace destructive testing methods. Mechanical tests remain necessary to directly determine the joint strength and to validate the informative value of non-destructively determined quality characteristics. Nevertheless, the investigated methods offer considerable potential as complementary testing techniques. They enable a detailed characterization of the joining zone without destroying the specimen and can therefore meaningfully extend the quality assessment of ultrasonically welded aluminum-copper dissimilar joints.

Overall, the results show that non-destructive detection of the bonding area represents a promising approach for assessing joint quality. Ultrasonic-based testing methods can contribute to a better understanding of the relationship between bonding area, process control, and mechanical load-bearing capacity. Thus, they provide a suitable basis for further investigations aimed at process optimization and quality assurance in ultrasonic metal welding.

6. Outlook

The present study demonstrates which non-destructive testing methods are generally suitable for detecting the bonding area in ultrasonically welded aluminum stranded conductor-to-copper terminal connections. Furthermore, it was evaluated to what extent characterization of the joining zone allows conclusions to be drawn regarding joint quality. In particular, the

comparison between the non-destructively determined bonding characteristics and the mechanical properties enables a differentiated assessment of the informative value of the investigated testing methods.

At the same time, the study raises further scientific questions. One central question is whether the testing methods investigated can also be transferred to other joint geometries and material combinations. This applies to sheet-to-sheet joints and busbar-to-terminal welds. Both similar and dissimilar material combinations should be considered to evaluate the applicability of the methods to different industrial joining systems.

In future work, it should also be investigated during which phase of the ultrasonic welding process the metallurgical bonding area is primarily formed. A time-resolved analysis of bond formation could contribute to a better understanding of the relationship between process control, interfacial activation and the resulting bonding area. In this context, it is particularly relevant to determine at which point in time the dominant mechanisms of bond formation begin and how these mechanisms are influenced by the process parameters.

These investigations should be combined with temperature measurements during the welding process. This would allow thermal process states to be directly linked to the formation of the bonding area. The combination of non-destructive testing, time-resolved process analysis and temperature measurement therefore offers the potential to gain deeper insight into bond formation during ultrasonic metal welding.

7. Declaration

The authors declare that they have no known financial conflicts of interest or personal relationships that could have influenced the work presented in this manuscript. All authors contributed to the conception and design of the study. Material preparation and data acquisition were carried out by Fabian Wohlwend. Data analysis was performed by Fabian Wohlwend. The initial draft of the manuscript was prepared by Fabian Wohlwend. All authors reviewed and commented on earlier versions of the manuscript. All authors have read and approved the final version of the manuscript.

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